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Nuclear Power Plants

New Insights

Edited by Nasser Sayed Awwad and Hamed Majdooa Algarni

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Meet the editors

Dr. Nasser Awwad obtained a Ph.D. in Inorganic and Radiochemistry from Ain Shams University, Egypt, in 2000, and a postdoctorate at Sandia National Labs, New Mexico, USA, in 2004. He was Associate Professor of Radiochemistry and Professor of Inorganic and Radiochemistry at the Egyptian Atomic Energy Authority in 2006 and 2011, respectively. He has been a professor at King Khalid University (KKU), Saudia Arabia, since 2011. He has authored two book chapters, edited six books, and published 300 journal papers. He has reviewed and supervised numerous Ph.D. and MSc students. He participated in twenty-five international conferences in South Korea, the United States, Lebanon, Kingdom of Saudi Arabia, Egypt, and India. He participated in six projects with King Abdulaziz City for Science and Technology (KACST), Saudia Arabia, and Sandia National Labs about the conditioning of radioactive sealed sources and wastewater treatment. Dr. Awwad is a leader and member of many research groups investigating the utilization of nanomaterials for the treatment of inorganic and organic pollutants. He is a member of the Arab Society of Forensic Sciences and Forensic Medicine and the Egyptian Society for Nuclear Sciences. He is the rapporteur of the Permanent Committee for Nuclear and Radiological Protection and the Permanent Committee of the Center of Talent and Innovation and Entrepreneurship, both at KKU. He is also a member of the Committee for the Development of International Cooperation Management and the Permanent Committee for the Development of Scientific Research Strategies and Policies, both at KKU.

Prof. Hamed Majdooa Algarni is the vice president of King Khalid University (KKU) for Postgraduate Studies and Scientific Research, Saudi Arabia. He received his MSc in Physics from KKU in 2007, and his Ph.D. from the University of York, UK, in 2014. Prof. Algarni received the Kathleen Mary Stott Prize for excellence in scientific research for the best Ph.D. from the University of York, in 2013. He received an academic distinction award (three times) from the Royal Embassy of Saudi Arabia, Cultural Bureau, London. He specializes in condensed matter physics, nanoscience, and nanotechnology, which includes growth, properties, and applications of nanostructured and biomaterials and optoelectronic devices. He has authored and co-authored more than 300 research articles in highly reputed journals.

Contents

Preface

This book discusses the current situation and future developments of nuclear power plants, including fission and fusion processes. Fission nuclear power continues to be an essential part of low-carbon electricity generation worldwide. For fast nuclear reactors, a substantial research and development effort is required in many fields—from material sciences to safety demonstration—to attain the envisaged goals. Fusion provides a long-term vision for efficient energy production. The fusion option for a nuclear reactor for efficient production of electricity has been set out by a focused European programmer.

This book deals with a variety of topics about nuclear power plants in six chapters. In Chapter 1, Nasser S. Awwad et al. establish an overview of the types of nuclear reactions and nuclear reactors. There are three types of nuclear reactions—dispersion elastic, low-energy nuclear reactions, and high-energy nuclear reactions—and four types of nuclear reactors—graphite reactors, uranium heavy water Reactors, material testing Reactors, and swimming pool reactors. Chapter 2 by Igor Volchyn et al. tests the hypothesis that holdings based on the principles of the circular economy for nuclear power plants and/or renewable energy sources with ammonia production plants can ensure the operating costs of electricity production with low pollutant emission and zero carbon dioxide emission at the level of coal thermal power plants. Chapter 3 by Md. Nur Salam and Md. Rokonuzzaman states that the physicochemical properties of water must be recovered to the recommended values of the World Health Organization (WHO), the US Public Health Service (USPHS), and power plant water chemistry guidelines. The values of raw water are very far from the recommended values for nuclear power plant operation. Thus, the water needs to be treated for use in boilers. Gravitation, carbon filtration, ion exchange method, and reverse osmosis (RO) are good ways to treat water before use in power plants. This chapter explores the water chemistry of the source water, the values of quality parameters, and the recommended values of technical guidelines. In Chapter 4, Vladimir Usanov and Stepan Kviatkovskii find ways to enhance the investment attractiveness of small and medium reactors (SMRs). The approach discussed in the chapter is based on the notion that mechanisms for financing a power system can be more flexible and efficient than those used to finance individual units. As an implementation of this general idea, the chapter presents a matrix investment model, in which management and financing are centralized. Results of the model application for evaluation of the economic indicators of SMR system construction are compared with the results provided by the levelized cost model. The results of the comparison show that the integration of a few SMRs into a financially united system opens up opportunities for shareholder income growth, creates favorable conditions for credit/private investors, and promotes public acceptance of nuclear power as a cost-effective energy option. In Chapter 5, Márta Juhász and Péter Kabai review the characteristics of main control room teams. In a hazardous working environment, human factors play a key role. The quality of teamwork affects people's psychological well-being, which has an impact on the quality of their work and their ability to work safely. In Hungary, at Paks Nuclear

Power Plant, the authors developed a questionnaire to measure the main control room's teamwork. The chapter presents the structure of the questionnaire and defines the scales created. The authors also base the development of teamwork on the analysis of video footage of a simulator exercise, which highlights the characteristics of successful teamwork. Both tools can be used to understand, analyze, and then improve control rooms' teamwork for more effective collaboration and performance.

Finally, in Chapter 6, Suha Ismail Ahmed Ali and Éva Lublóy examine the use of heavyweight concrete, including its components and qualities. Concrete can be organized into three primary categories: conventional, heavyweight, and lightweight concrete, depending on density. With a density of 2400 kg/m3, conventional concrete, sometimes referred to as ordinary concrete, is the most commonly used variety. Conventional concrete is widely used for a variety of construction projects, such as foundations, buildings, bridges, and pavements. When making heavyweight concrete, which has a density of more than 2600 kg/m3 and can reach 3850 kg/m3, heavy aggregates like magnetite, barite, or iron ore are added. This kind of concrete has great mechanical qualities, outstanding fire resistance, and remarkable endurance. It is used in specialist industries such as radiation treatment centers, nuclear power plants, and structural counterweights.

We hope this book will inspire readers, researchers, and scientists to further their research and knowledge of nuclear power plants. Finally, we would like to thank the contributing authors and the staff at IntechOpen. We hope this work will contribute much knowledge to nuclear power plants.

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Chapter 1

Introductory Chapter: Overview about the Types of Nuclear Reactions and Nuclear Reactors

Nasser Sayed Awwad, Gamil A.A. Al-Hazmi and Hamed Majdooa Algarni

1. Introduction

1.1 Types of radioactive decay series

The heavy radioactive elements are divided into four series, and the series is usually called the parent element. Three of these chains start with heavy, naturally occurring radioactive elements: thorium, uranium, and actinium. The fourth series begins with neptunium, which is an artificial element.

The reason for having only four groups is that as a result of alpha decay, there is a decrease in A by 4, while beta decay does not change the value of A.

The radioactive elements found in nature, as is known, have a longer half-life than neptunium. The radioactive decay of these elements is carried out by releasing α and β radiations, as they produce radioactive elements and are successively stable until reaching the stable element.

The series is arranged as follows:

- Thorium series (4n)
- Neptunium series (4n + 1)
- Uranium series (4n + 2)
- Actinium series (4n + 3)

1.2 Nuclear reactions

Rutherford showed in 1915 that nuclear reactions can be carried out by bombarding the nuclei of some substances with high-energy particles. Rutherford described the following nuclear reaction:

$$ {}_7N^{14} + {}_2He^4 \rightarrow \left({}_9F^{18}\right) \rightarrow {}_8O^{17} + {}_1H^1 + Q \tag{1}$$

This reaction was considered the first nuclear reaction to take place in the laboratory, after which many nuclear reactions were conducted.

1.3 Types of nuclear reactions

1.4 Dispersion elastic

Elastic scattering occurs at all energies and for all particles. The event is called elastic scattering if the energy value of the particles does not change and if the sum of the kinetic energies of the projectile and the target nucleus remains constant.

Elastic scattering of charged particles with energies below the Coulomb barrier to the target nucleus is the famous Rutherford scattering experiment. At high energies, the probability of the projectile approaching the surface of the target nucleus and penetrating the Coulomb barrier increases, and thus, the nuclear forces contribute to elastic scattering. Elastic scattering of neutrons at all energies occurs only as a result of the influence of nuclear forces.

2. Types of energy at nuclear reactions

2.1 Low-energy nuclear reactions

These reactions are less than 40 Mev. The reaction of the disintegration of the nitrogen nucleus with alpha particles represents a series of reactions in which the nucleus captures an alpha particle, forming a compound nucleus that instantly disintegrates into a new nucleus with the emission of a proton. These interactions are known as (p, α) interactions.

Examples of these interactions that have been studied include:

$$B^{10}\ (\alpha, p)\ C^{13} \tag{2}$$

$$Al^{27}\ (\alpha, p)\ Si^{30} \tag{3}$$

$$S^{32}\ (\alpha, p)\ Cl^{35} \tag{4}$$

$$K^{39}\ (\alpha, p)\ Ca^{42} \tag{5}$$

When beryllium is bombarded with alpha particles, a neutron is emitted, and a new nucleus is formed, Be^9 (α,n) C^{12}, and bombardment of beryllium with alpha particles and the subsequent emission of neutrons is one of the nuclear reactions of the type (α, n). Examples of these reactions are:

$$Li^{7}\ (\alpha, n)\ B^{10} \tag{6}$$

$$N^{14}\ (\alpha, n)\ F^{17} \tag{7}$$

$$Al^{27}\ (\alpha, n)\ P^{30} \tag{8}$$

In many of these artificial nuclear reactions, the resulting nucleus is radioactive. In the last reaction, for example, the isotope P^{30} is formed, which is unstable and breaks up by the emission of a positron (this reaction was known as the positron preparation experiment by Giulio and Curie in 1934 with a half-life of 2.5 minutes.

Protons can be used as projectile particles, as in the following reaction:

$$_3Li^7 + _1H^1 \rightarrow (_4Be^8) \rightarrow 2_2He^4 + Q \tag{9}$$

That is, the compound nucleus formed as a result of the capture of a proton by the lithium nucleus splits into two bodies of alpha particles, which move in almost opposite directions.

A very large number of reactions were seen, in which the deuterons (deuterium nuclei) were the projectiles. These interactions can be classified according to the type of particle. The particles that are emitted from the compound nucleus are formed as a result of the capture of deuterons. The use of deuterons as shells has led to the processes (d, p), (d, n), (d, α) with all the elements of the periodic table. One of the important interactions is the disintegration of sodium by bombarding deuterons. In this case, the reactions were seen:

$$_{11}Na^{23}\ (d, n)_{12}Mg^{24} \tag{10}$$

$$_{11}Na^{23}\ (d, p)_{11}Na^{24} \tag{11}$$

The reaction (d, n), the magnesium-24 nucleus formed in a stable state. But in the reaction (d, p), the radioactive sodium-24 is formed, which decays by emission of β-negative particles into Mg-24, which is left in an excited state and decays to the ground state by emission of two gamma-ray photons in two steps, as shown in the following **Figure 1**:

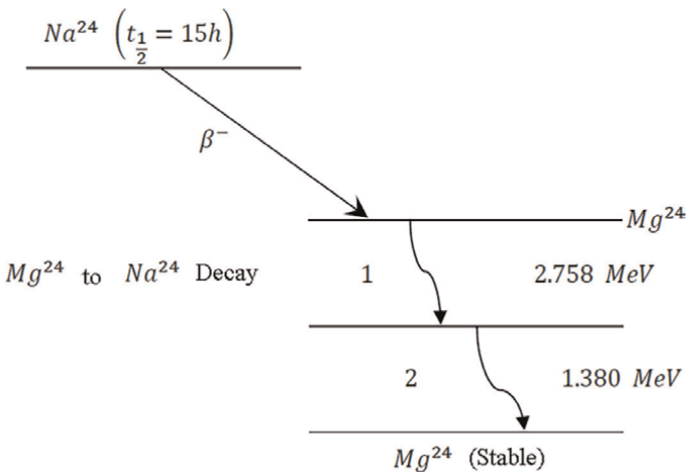

Figure 1.
Diagram shows how radioactive sodium-24 decays.

Since neutrons are free of electric charge, they are very effective in penetrating nuclei and causing nuclear transformations. Not only high-energy neutrons are able to penetrate the nucleus, but also slow neutrons are also very effective, and the reaction B^{10} (n, α) Li^7 is used as a neutron-sensitive detector.

2.2 High-energy nuclear reactions

The 50 Mev is a boundary between low energy and high energy. The study of nuclear reactions that occur with high-energy missiles revealed several new types of processes, which requires a significant modification of the concept of the formation of the compound nucleus to explain some of these processes.

For example, if the reaction takes place:

With low-energy deuterons, a complex nucleus is formed, and neutrons are emitted from the target in all directions. But if high-energy deuterons are used as projectiles, the dominant direction of neutrons emitted with very high energy is the forward direction.

When precise targets such as beryllium, aluminum, copper, and others were bombarded with high-energy deuterons (more than 100 Mev), a narrow beam of neutrons was seen rushing in the forward direction with very high energy. The phenomenon was explained by the fact that the deuteron does not affect the nucleus but passes close to it, so the proton is extracted from it and the neutron continues to travel at approximately the same speed as the deuteron.

Due to the high speed of the deuteron, the interaction time between it and the nucleus is very small to the extent that the change in the neutron's motion in this extraction process is very small, and this process represents an interaction (d, n).

We also refer here to a phenomenon related to extraction seen in low-energy cases in which the energy of the deuteron is lower than the Coulomb barrier, but it leads to a process (d, p). This phenomenon occurs when the deuteron passes close to the nucleus, at a distance between 3R–R, where R is the nuclear radius. Oppenheimer and Philips have interpreted it.

These results are arising from the polarization of the deuteron in the Columbian field of the nucleus. In this case, the columbic force arising between the target nucleus and the deuteron proton is sufficient to break the bond between it and the neutron. So the proton is repelled and the neutron is captured in the nucleus, and this process is a special type of (extraction) called the Oppenheimer process. Phillips and the reverse process of extraction is in which a high-energy projectile, such as a proton, neutron, or deuteron, captures another particle while passing near the nucleus [1].

These interactions differ from those in which a compound nucleus is formed in that the particle formed in the "capture" process has a large forward movement, while the particles emitted from the compound nucleus show a symmetrical movement distribution in all directions relative to the center of mass.

An example of a "capture" process is:

$$C^{13}\ (d, t)\ C^{12} \tag{12}$$

Another important process is seen when high-energy particles collide with the target, and this process includes the emission of several nuclear parts, such as protons, neutrons, or alpha particles, and this process is known as "rupture." When a target with a medium atomic weight is bombarded with high-energy particles, the products of a rupture usually include a wide range of mass numbers and atomic numbers ranging from 39 to 52 and mass numbers ranging from 124 to 87.

3. Types of nuclear reactions

3.1 Nuclear fission

Whereas, nuclear reactions are of the type of nuclear fission, fusion, or nuclear fusion.

In 1939, after a series of very precise chemical experiments, Hahn and Straßen found that one of the elements formed by bombarding uranium with neutrons is an isotope of the element Ba (Z = 56). Accordingly, the two scientists suggested that it is possible that the process that begins with bombarding uranium with neutrons is a process in which the formed uranium nucleus is considered unstable and splits into two nuclei of medium atomic mass. If one of the two nuclei formed is a barium nucleus (Z = 56), then the other must be a krypton nucleus (Z = 36). This type of fragmentation process in which the heavy nucleus splits into two nuclei close in mass is called nuclear fission. Within 2 years of the discovery of nuclear fission, the range of experiments expanded to include the fission of thorium and protactinium. Much more energy is released in the nuclear fission process than has been seen in any previous nuclear or atomic process.

In addition to the release of energy, the fission of uranium is accompanied by the emission of several neutrons, and it seems clear that it is possible to use those neutrons to create the appropriate conditions to cause nuclear fission of other uranium nuclei and then a chain reaction can be started that can release huge amounts of energy. The following figure represents an illustration of the fission of Uranium-235. The large energy released in such reactions can be used in power plants or nuclear weapons [2].

The fission of uranium-235 can be represented by the following equation:

$$_{92}U^{235}+_{0}n^{1}\rightarrow_{92}U^{236}\rightarrow_{56}Ba^{191}+_{36}Kr^{92}+3_{0}n^{1}+Q \qquad (13)$$

where Q is the energy released in the reaction and is the difference in mass between the initial and final particles [3].

It can be caused by both slow and fast neutrons, and Bohr and Wheeler's used the liquid-drop model of the nucleus in their theory of nuclear fission. According to this theory, nuclear fission occurs in two stages:

1. The complex nucleus in which energy is temporarily stored is distributed over the degrees of freedom of nuclear particles in a manner similar to thermal turbulence in a liquid.

2. A sufficient portion of this energy is converted into potential energy to change the shape of the compound nucleus in a way that leads to its fission.

The fission process can be depicted as shown in **Figures 2** and **3**. Where the drawing (a) depicts the compound nucleus with mass number A and atomic number Z as a liquid droplet in a state of high excitation, as a result of the forces acting between

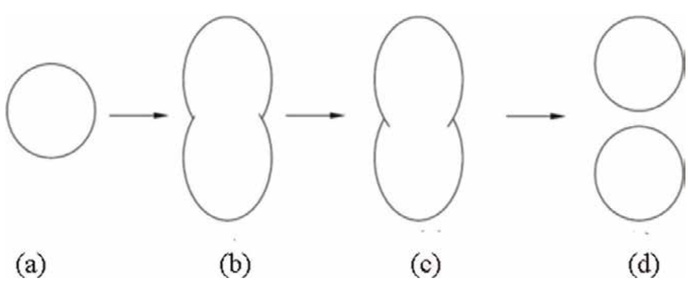

Figure 2.
Diagram showing how uranium-235 is fission.

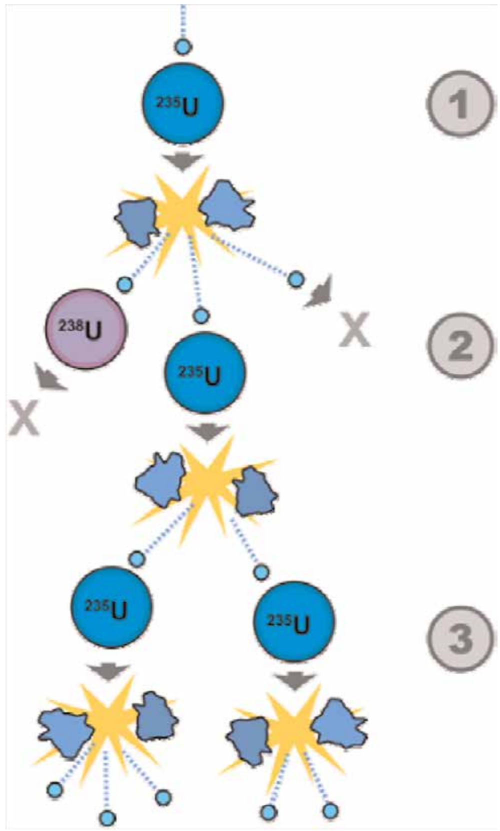

Figure 3.
Schematic diagram of nuclear fission.

the nucleons, the liquid drop changes its shape as it is in (b). Then reaches a certain stage at which it takes the form shown in (c). This structure is unstable. If the excitation energy is sufficient, then the liquid drop is separated into two drops at some point in the thin neck and two nuclei are formed, as shown in (d).

3.1.1 Serial reaction

After the discovery of uranium and nuclear fission, scientists realized that a new source of energy could be easily available if more than one neutron was emitted for each fission neutron. The average number of neutrons released in fission has been determined by slow or thermal neutrons, and the accepted values are now 2.5 neutrons for each fission of a uranium 235 nucleus. The first generation of neutrons will lead to the production of four neutrons, and the second generation will lead to the fission of four uranium nuclei and produce eight neutrons, thus becoming 64, 32, 16 since these fission are fast. The fission product will be enormous, and if we know that each fission produces 200 Mev, the amount of energy will be enormous.

As a result of the emission of a neutron or more on average in each fission, a chain reaction may occur (i.e., it will continue on its own) in a block of fissionable material.

An atomic bomb is defined as a means designed to produce an increasingly explosive chain reaction modified to the point of explosion.

When the mass of the target sample is very small, a number of neutrons will not be absorbed. This situation leads us to define the so-called critical mass for any fissionable material, which is the smallest mass of fissionable material sufficient to continue the reaction.

In the event that the mass of the diffuse material is very large, i.e., supercritical mass, the number of fissile nuclei will double, and this is what is done in atomic bombs where, if necessary, two separate masses of fissile material can be combined. So that we obtain a supercritical mass, the chain reaction results in the fission of nuclei matter and gets a great deal of energy.

The system or group is called to arrange the fissionable and non-fissionable materials in it so that the serial reaction can proceed in a controlled manner in a nuclear reactor.

The nuclear reactor is a source of the products of the fission process, which are energy, neutrons, and radioactive isotopes. As we mentioned earlier, the energy released, which is in the range of 200 Mev for each fission, occurs for one atom, and this fission is considered a source of atomic energy on an industrial scale. As a neutron source, a nuclear reactor can supply us with a large number of neutrons per unit of time, distributed over a wide range of energies.

Since fission does not occur alone in heavy nuclei but captures the nucleus of the neutron in the reaction (n, α). It can, by capturing the neutron, produce many useful isotopes and convert the elements to each other, for example, the production of plutonium from uranium-238 or the production of C^{14} from N^{14} or the fissionable production of U^{233} from $Th^{232,}$ and so on.

3.1.2 Nuclear fission reactor

A nuclear fission reactor is a machine by which a chain reaction can be controlled. In power plants, a nuclear reactor is used to obtain heat that can be used to generate electricity. Inside the reactor, fuel rods and control rods are arranged periodically. The fuel rods contain fissionable materials, and these rods differ from one reactor to another. In the case of a normal water-cooled reactor, the fuel rods consist of uranium oxide manufactured in the form of pellets placed in tubes of zirconium alloy. It is known that the uranium found in nature contains 99.3% of U^{238}, and the rest is about 0.7% of U^{235}, and since the latter is fissionable, it is necessary to enrich uranium-235 so that its percentage becomes about 3%. Control rods are usually made of boron, hardened boron, or other materials [4]. The rods absorb neutrons, and thus, the reaction can be calmed and controlled. This is done by changing the extent of the control rods compared to the fuel rods so it is possible to increase or decrease the absorption of neutrons or even stop the reaction, see **Figure 4**.

As for the moderator, it is the substance that reduces the speed of neutrons, and high-speed neutrons are mostly absorbed by uranium-238, while slow neutrons are preferentially absorbed by uranium-235. The serial reaction can be kept going even if the U^{235} ratio is low. Heavy water, light water, and graphite coal can be used as moderators.

In the light water reactor, the water performs two tasks: cooling and cooling. In this reactor, the water temperature is about (350°) at a pressure of (150 atm). It is known that the water will not boil at this temperature as long as the pressure applied is

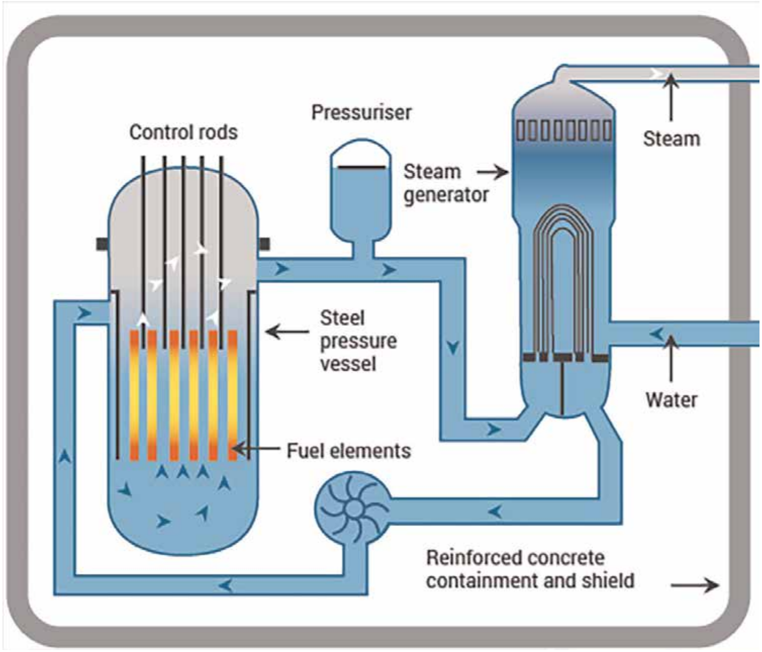

Figure 4.
Nuclear fission reactor.

what was mentioned. The heated water is transferred to a heat exchanger, where the heat is used to generate steam that drives the turbines and for this, we get electricity.

Spent fuel is a major problem for the nuclear industries. Chemical methods can be used to separate the components of spent fuel to obtain the required materials and use them again. However, the treatment plants are considered expensive and have advanced technology and therefore not all countries can obtain them; in addition to the fear of the countries that own, a technology that other countries will obtain materials such as plutonium-239 of the fuel used could be used as a nuclear weapon. This isotope is obtained when uranium-238 is bombarded with neutrons.

Plutonium-239 is similar to uranium-235 in that it is fissionable. Whether the spent fuel is treated or not, this fuel represents a major problem in power plants that rely entirely on nuclear energy because, over time, large quantities of nuclear waste accumulate, which poses a great danger to the environment, and therefore, it must be disposed of in one way or another. One of the proposed methods of disposal is burying it in abandoned mines, far and deep, while taking the necessary precautions to prevent its infiltration into the soil or water sources with approximately the same percentage, in addition to a small amount of energy obtained as a result of the fission of (Pu^{239}), which was obtained from the previously mentioned reactions.

3.1.3 Breeder reactor

Plutonium-239 is fissionable, such as (U^{235}), and the generator reactor works by reducing the amount of moderators. So, it produces some fast neutrons that convert (U^{235}) to (Pu^{239}), and in this way, the first available in nature can be converted into a

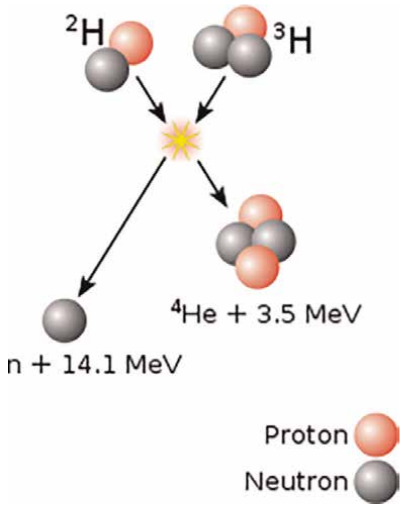

Figure 5.
Conversion of hydrogen to helium (carbon cycle).

source of energy from modern reactors. The generator reactor A fast breeder reactor does not use sedatives so that the largest amount of Pu can be produced. The latter gets to stop the generator reactor from time to time and treat the unspent fuel, and Pu can be used to produce fuel for the other reactors.

3.2 Nuclear fusion

There are serious attempts to obtain nuclear energy through nuclear fusion, which is the process by which two lighter nuclei are fused to obtain a heavier nucleus. This process is similar to the processes occurring in stars such as the sun. Fusion processes release more energy than they obtain from nuclear fission. In fusion reactions, very large activation energy must be provided in order for the merger to take place, and nuclear fission is used to provide such energy. The hydrogen bomb is based on nuclear fusion [5, 6].

The conversion of hydrogen to helium is preferred because the binding energy per nuclear particle is higher in helium than in hydrogen, and the conversion of hydrogen into helium is a fusion reaction, see **Figure 5**.

It is believed that the energy emitted by the sun and other stars results from the conversion of hydrogen into helium in a series of nuclear reactions called the carbon cycle. These reactions take place in the interior of the sun, where the temperature reaches a very high point so that the atoms are completely stripped of their electronics.

3.2.1 Carbon Cycle

$$_6C^{12} + {}_1H^1 \rightarrow {}_7N^{13} \tag{14}$$

$$_7N^{13} \rightarrow {}_6C^{13} + \beta^+ \tag{15}$$

$$_6C^{13} + {}_1H^1 \rightarrow {}_7N^{14} \tag{16}$$

$$_7N^{14}+_1H^1\rightarrow_8O^{15} \quad (17)$$

$$_8O^{15}\rightarrow_7N^{15}+\beta^+ \quad (18)$$

$$_7N^{15}+_1H^1\rightarrow_6C^{12}+_2He^4 \quad (19)$$

The net reaction is the conversion of four hydrogen ions into a helium ion and two positrons:

$$^1H_1\rightarrow^2He_4+2\beta+E \quad (20)$$

Since the net reaction belongs to hydrogen as a single reactant, this process has been referred to as (hydrogen combustion).

Nuclear fusion has an advantage over nuclear fission, and the successful development of a fusion reactor will provide a lasting solution to human energy problems. Because he has at his disposal impermeable fusion materials, the rate of energy production in the fusion reaction is higher, and it is not accompanied by the formation of radioactive products that pollute the environment.

Fusion reactions have been carried out in the laboratory using accelerators. For example, deuterons (heavy hydrogen nuclei) can be accelerated and directed toward targets containing H^2 itself or tritium H^3 and the reactions are:

$$_1H^2+_1H^2\rightarrow_2He^3+_0n^1\rightarrow \quad (21)$$

$$_1H^2+_1H^3\rightarrow_2He^4+_0n^1 \quad (22)$$

The kinetic energy of the projectile must be high to overcome the forces of repulsion with the positive charges in the nucleus and to interact with a great advantage, which is the availability of deuterium in large quantities in nature, i.e., about (0.015%) of ordinary hydrogen and nuclear accelerators cannot be used to complete fusion reactions for applied purposes due to the presence of many technical problems. At this temperature, the atoms can ionize completely, and we get what is called plasma.

Plasma is a homogeneous mixture of atomic nuclei, and electrons move very quickly and randomly. For this reason, it is necessary to develop fusion technology for the development of plasma research at high temperatures. It is for this reason that a magnetic field is used to prevent plasmas from contacting matter, and in recent years, lasers have been used to cause fusion processes.

4. Types of nuclear reactors

4.1 Graphite reactor

The first graphite reactor was built in the United States in 1943. The reactor core, which has a cubic capacity, consists of 24 feet a number of graphite pieces equipped with more than a thousand nuclear fuel channels. The fuel consists of uranium metal in the form of aluminum-coated rods. The fuel is cooled with air, and the graphite works as a reflector. The core is surrounded by a thick 7-foot concrete shield and equipped with channels for experiments and other control rods. This type of reactor is used to produce plutonium.

$$_{92}U^{238}+_0n^1\rightarrow\ _{92}U^{239}\text{---}\beta\rightarrow_{93}Np^{239}\text{---}\beta\rightarrow_{94}Pu^{239} \quad (23)$$

4.2 Uranium heavy water reactors

The reactor core consists of a cylindrical tank with a diameter of 2 meters and contains 7 tons of heavy water D_2O. The cross section of the absorption of neutrons is small, so the moderation of neutrons slows down a few, as this reactor is smaller than the graphite reactor and requires less fuel. The reactor is controlled by plates of cadmium. The reactor is cooled and heavy water is pumped between the reactor core and the heat exchanger.

4.3 Material testing reactors

This type of reactor is mainly used in examining and studying the behavior of residues in high levels of radiation and uses uranium enriched with a percentage of up to (93%) (U^{235}) as fuel. Ordinary water is used as a lubricant and coolant at the same time. Beryllium is used as the first reflector, and graphite is used as a second reflector, with a thickness of 4 feet. The protective shield is made of concrete, with a thickness of 9 feet. The reactor is equipped with channels for checking the materials, and the control of the nuclear reactor is carried out with rods of cadmium.

4.4 Swimming pool reactors

This type of reactor is similar to material testing reactors with its low price and low complexity. The reactor core is suspended in a pool of water to a depth of 25 feet, and the water acts as a moderator, coolant, reflector, and protective shield. The fuel is composed of uranium enriched with uranium-235 at a rate of (93–20%), and the critical mass of this type of reactor is estimated at 2500 g U^{235}; the control rods are cadmium and carbon carbide (**Figure 6**).

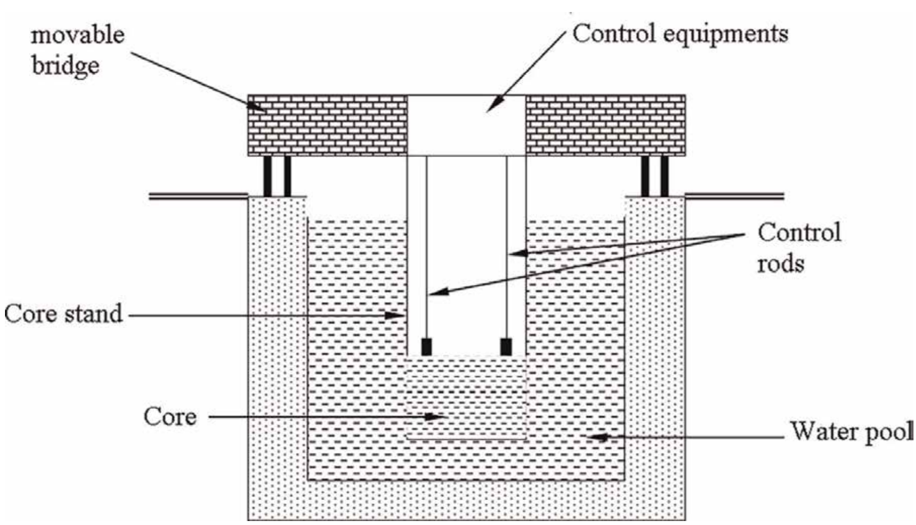

Figure 6.
Scheme of the swimming pool reactor.

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Chapter 2

Creating the Holdings of Nuclear Power Plants and/or Renewable Energy Sources with Ammonia Production Plants on the Base of Circular Economy

Igor Volchyn, Danylo Cherevatskyi, Vitaliy Mokretskyy and Wlodzimierz Pzybylski

Abstract

The COP26 conference declared the end of the "coal" era in the economy. The coal thermal power plants (TPPs) are subject to closure. For many macroeconomics, this is a large energy and economic losses. But the fleet of coal-fired thermal power plants can be saved by switching to burning ammonia base fuel an instead of coal. Ammonia has a hydrogen content of 17.6% and an almost unlimited raw material base. The convenience and experience of transportation, storage, and processing of ammonia make it a promising source of energy storage. But ammonia produced using water hydrolysis is more expensive than coal as a fuel. The purpose of this study is to test the hypothesis that holdings based on the principles of the circular economy for nuclear power plants and/or renewable energy sources with ammonia production plants are able to ensure the operating costs of electricity production with low pollutant emission and zero carbon dioxide emission at the level of coal thermal power plants.

Keywords: nuclear power plant, circular economy, ammonia, combustion, thermal power plant, energy and chemical holding, economics

1. Introduction

Combating the global climate change and protecting the environment are becoming one of the main priorities in world politics, as confirmed by the decisions of the Rome G20 summit [1] and the 26th Conference of the Parties to the United Nations Framework Convention on Climate Change COP26 in Glasgow, UK [2], which took place in the fall of 2021. The COP26 conference declared the end of the "coal" era in the economy in the near future. Even new coal-fired thermal power plants (TPPs) with the best environmental performance are subject to closure. This can be a large energy and economic loss for many countries. For example, the installed electrical capacity of the Integrated Energy System of Ukraine is about 51 GW, and almost 54% of it is coal-fired thermal power plants. But the fleet of coal-fired thermal power plants can, in principle, kept in service if coal is replaced by carbon-free hydrogen-based fuel.

The energy systems, use hydrogen, although considered the most promising in the world [3], have major technical and economic problems due to the difficulty in its storing and transporting [4]. But this can be corrected by switching to the use of ammonia (NH_3) as a hydrogen-containing fuel [5]. The Japanese power companies have already started implementing plans for a phased transition to burning ammonia in the coal-fired power generation [6]. Test combustion of ammonia with coal at an existing 1,000 MW power unit at Hekinan TPP confirmed the absence of significant negative impact on the unit itself [7] and that ammonia is able to act as an ecologically suitable substitute for coal [8].

High hydrogen content (0.176 kg of H_2 per 1 kg of ammonia), an almost unlimited raw material base, convenience and extensive experience in transportation, storage, and processing, makes ammonia a promising energy carrier for thermal power plants.

But the problem is the high cost of "green" ammonia. According to the conventional classification, the ammonia can be "gray"—obtained from hydrogen using the technology of steam reforming of natural gas or coal and nitrogen from the air, "blue"—obtained on the basis of hydrogen using the technology of steam reforming of natural gas or coal with the application of carbon capture and storage technologies, "green"—on the basis of hydrogen obtained by electrolysis due to the electricity of renewable sources, and "yellow"—on the basis of hydrogen obtained using electricity produced at the nuclear power plants [9].

The ammonia used at the Mizushima TPP, Japan, was "blue." It was produced by the state oil and gas company Saudi Aramco in Saudi Arabia. Green ammonia is projected to be available in many locations for less than USD 400/t in 2040, with the potential to decrease to below USD 300/t if water electrolysis costs are reduced [10]. At a price of 450 EUR/t, "green" ammonia produced in Chile using the Haber-Bosch synthesis technology can make even an investment project to export it by sea to Japan cost-effective [11]. However, prices in electricity markets are much lower than in fertilizer markets.

Thus, the problem of prolonging the operation of coal-fired power plants can be transferred from the ecological to the economic level: Ammonia produced by electrolysis is much more expensive than coal. But a drastic reduction in ammonia production costs is achievable if it is:

a. "yellow" ammonia, that is, using electricity from nuclear power plants and

b. produced on the basis of circular economy [12].

This determined the purpose of the research: to perform an analysis of the economic efficiency of investment projects for the creation of energy-chemical holdings, which include nuclear power plants and ammonia-fired thermal power plants.

2. Study methods

The task of the research is to analyze the efficiency of the investment project—to check the ability of the annual cash flows from the holding's activities to cover the capital investments due to the purchase of electrolyzers and other ammonia production equipment during the period of the project.

The value of total investment costs net present value (NPV) is determined by the formula [13]:

$$\mathrm{NPV} = -\mathrm{Inv} + \sum_{0}^{T} \frac{\mathrm{B}_t - C_t}{(1+r)^t} \tag{1}$$

where Inv is the investment amount; B_t is total revenues for year t; C_t is total costs for year t; t is the corresponding year of the project; T is the full term of project implementation; r is the discount rate (unit fraction).

An investment project is considered profitable for the investor if NPV ≥ 0.

The difference between the total annual income B_t and expenses C_t is the annual cash flow of the project—cash flow (CF_t):

$$\mathrm{CF}_t = B_t - C_t, \tag{2}$$

With "amortizing" repayment of credit resources, the payments are made in equal amounts regularly and they include a certain part of the loan amount and interest. Along with the last installment, the loan amount is repaid. The specified approach can serve as a justification for the assumption of equality of annual cash flows (annuities) for the project. In this case, the break-even condition of the project corresponds to the value of a certain break-even annuity

$$\mathrm{CF}_{\mathrm{NPV=0}} = \frac{\mathrm{Inv}}{\sum_0^T \frac{1}{(1+r)^t}}. \tag{3}$$

That is, any excess of the current annual cash flow of the annuity, determined by the given volume of investments and the rate of the cost of capital according to formula (3), will ensure the break-even of the project

$$\mathrm{CF}_t > \mathrm{CF}_{\mathrm{NPV=0}}. \tag{4}$$

The annual cash flow CF_t, million EUR or MEUR, at a thermal power plant, where electricity is obtained by burning fuel, is calculated on the basis of the volume of electricity released into the network, E, GWh, according to the formula

$$\mathrm{CF}_t = p \times \left(1 - \frac{w}{p}\right) \times E \bullet 10^{-3} \tag{5}$$

where p is the electricity price, EUR/MWh; w is the cost of generating electricity at the TPP, EUR/MWh.

The application of the production function allows you to link the amount of electricity released into the network from the TPP with fuel consumption. It can be described with great reliability by logarithmic dependencies [14] of the type:

$$E = L \bullet \ln(F) + M, \tag{6}$$

where E is the annual volume of electricity released from the thermal power, GWh; L, M are the function coefficients; F is the annual volume of fuel used, kt of coal equivalent.

3. Study results and their discussion

Obtaining the "green" or "yellow" ammonia using the Haber-Bosch process is energy-intensive: In the article [15], for example, authors are talking about a specific energy consumption of 10.43 kWh/kg NH3. It is impossible to radically reduce this indicator on the existing technological basis, although the freedom of maneuver remains. Thus, the nuclear power plants are usually unsuitable for deep regulation of power generation operating modes. Therefore, the usual nighttime decrease in demand for electricity from nuclear power plants requires the involvement of unusual consumers, which could be electrolyzers designed for hydrogen production. Electric energy from a nuclear power plant, used to be waste, enters the market, where it is purchased by a chemical plant for the production of ammonia [16]. The produced "yellow" ammonia is purchased on the appropriate market by the reformed thermal power plant in order to generate electricity during times of shortage of energy resources and sell it on the electricity market (**Figure 1**).

The market relations between business entities allow the difference in tariffs to significantly reduce the cost of obtaining hydrogen by water electrolysis. The stability of load regimes of the generating fund, on the one hand, and the economic effect on hydrogen production processes, on the other, create synergy in the system. The number of publications by scientists from different countries confirms the adequacy of such logic [17–19], but it is valid only up to the stage of obtaining secondary energy resources. The high market value of ammonia does not allow solving the problem of to keep in use the coal-fired power generation park.

wA fundamentally different approach opens up following the principles of the circular economy. Produced by nuclear power plants against insufficient demand: Unused electricity is lost, that is, it becomes waste. The circular economy based on the three Rs (reduce, reuse, and recycle) [20] can become a solution to an almost intractable commercial situation, if recycling of electricity is used as waste for direct, almost free powering of electrolyzers. This is possible in the case of a holding that combines a nuclear power plant, a plant for the production of hydrogen (ammonia) and a thermal power plant. **Figure 2** shows the scheme of the specified vertically integrated complex.

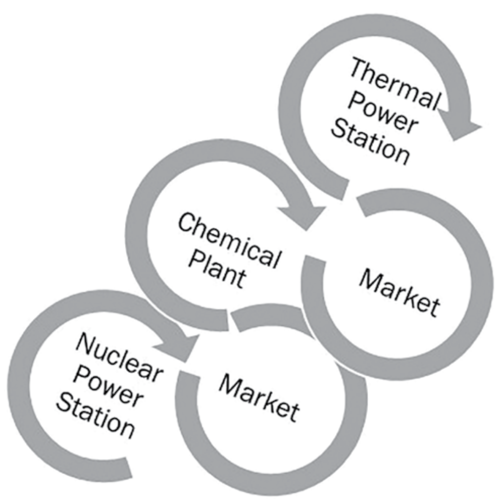

Figure 1.
Market system of interaction of elements of the energy-chemical system.

The principles of the circular economy remain valid even in the case of using energy-generating systems based on renewable energy sources. Electricity produced by wind or photovoltaic (solar) power plants, but not in demand, is the same waste as electricity produced by nuclear plants during the nighttime peak—recycling of these resources allows you to radically reduce the costs of obtaining hydrogen/ammonia.

According to Osman et al. [15], the use of nuclear power plants for powering electrolyzers is expedient in a cyclical, not in a continuous mode, with the interruption of the water electrolysis process after approximately 6–7 h, which corresponds to the nighttime failure of electricity consumption in the network and the off-peak period of operation of nuclear reactors. The duration of operation of electrolysis plants in this mode during the year can reach 2,345 h from 8,040 h/year in the 24-hour electrolysis mode.

The lower heat value of ammonia is 18.6 MJ/kg, which is less than that of bituminous coal (22.5–26.8 MJ/kg), and this determines the need for greater fuel consumption in the event of the transition of the coal power plant to the consumption of other fuels.

It is proposed to choose the Prydniprovska TPP, which has 7 power units with a total installed electrical capacity of 1,765 MW, as the object of research. The main fuel is Donetsk anthracite.

The production function of Prydniprovska TPP under the conditions of using coal (Fc) and ammonium fuel (Fa) is described by the formulas

$$E = 2{,}988 \bullet \ln(\mathrm{Fc}) - 17{,}746 \quad (7)$$

$$E = 2{,}988 \bullet \ln(\mathrm{Fa}) - 18{,}912 \quad (8)$$

and the actual production function of Prydniprovska TPP has the form shown in **Figure 3**.

When calculating the production function of a thermal power plant under the conditions of its consumption of ammonium fuel, a 7% fuel saving was adopted while maintaining the volume of released electricity due to the elimination of means of dedusting and desulfurization of flue gas [21].

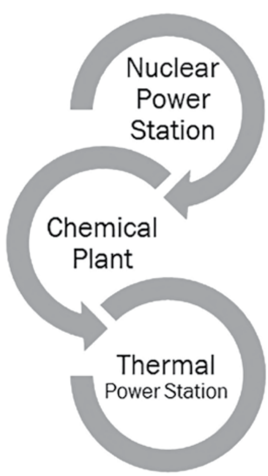

Figure 2.
Layout of a vertically integrated energy and chemical holding.

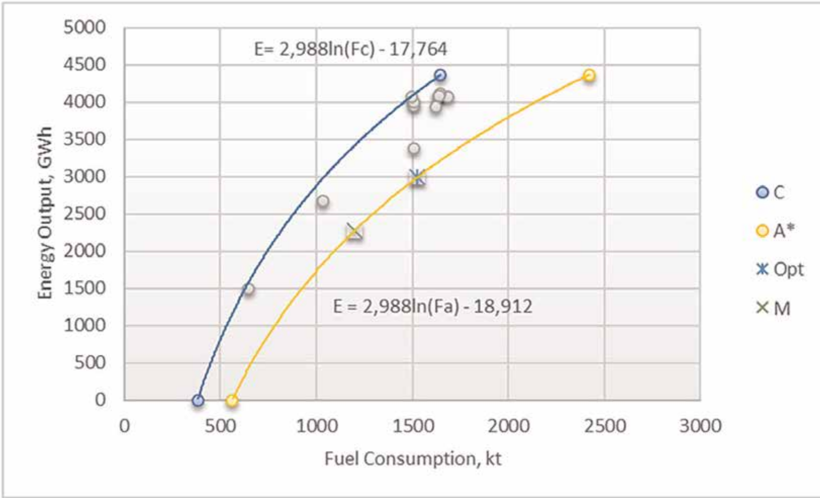

Figure 3.
Production function of Prydniprovska TPP under the condition of using coal or ammonium fuel as fuel.

The points in **Figure 3** show the current annual data on the operation of the thermal power plant in terms of electricity generation and fuel consumption; the curve contouring the specified points is actually a production function. Points below the production function indicate inefficient use of resources and production assets. Curve C is a graph of the production function of the thermal power plant when it is fed with coal fuel, and curve A is with ammonium fuel.

According to the formula of the production function, the optimal mode of fuel consumption of Prydniprovska TPP according to the criterion of the maximum specific release of electricity per unit of fuel when using ammonium fuel is approximately 1,500 kt of coal equivalent, which corresponds to the release of 3,000 GWh of electricity (2.0 MWh/t)—the ***Opt*** point on the production function. For coal, the maximum ratio of electricity output to fuel consumption is 2.8 MWh/t (3,000 GWh per 1,038 kt).

The HØST PtX Esbjerg company's project with a production of 600 kt of green ammonia per year with an investment of 1,400 MEUR, an electrolyzer capacity of 1 GW, and an annual electricity consumption of 5,000 GWh provides an idea of the scale of production [22]. The ammonium resource base of Prydniprovska TPP requires the construction of almost three (2.7) such plants.

Let us take the number of chemical plants producing ammonia equal to 2. In this case, Fa = 600 × 2 = 1,200 kt; E = 2.270 GWh per year (the ***M*** point on the production function).

The annual cash flow of the energy-chemical complex for ammonia production and combustion at the base of the Prydniprovska TPP is equal to

$$CF_t = p \times \left(1 - \frac{w}{p}\right) \times \frac{2{,}988 \bullet \ln(\text{Fa}) - 18{,}912}{1{,}000}, \text{MEUR} \tag{9}$$

where p is the electricity price, EUR/MWh; w is the cost of generating electricity at the TPP, EUR/MWh; Fa is the optimal consumption of ammonium fuel, kt/year.

The annual break-even annuity for the holding as a whole

$$CF^{s}_{NPV=0} = n \bullet CF^{1}_{NPV=0} \tag{10}$$

where $CF^{S}_{NPV=0}$ is the break-even annuity of a holding with n plants producing ammonia; n is the number of plants producing ammonia for supply to the thermal power plan; $CF^{1}_{NPV=0}$ is the break-even annuity for one ammonia plant.

Provided Inv = 1,400 MEUR; r = 0.12; T = 25 years, the break-even annuity for one ammonia plant is 178 MEUR, and for the energochemical holding in general

$$CF^{s}_{NPV=0} = 2 \times 178 = 356 \text{ MEUR}. \tag{11}$$

Figure 4 shows the dependence of the electricity price, the excess of which ensures the break-even operation of the energy-chemical holding at different levels of management efficiency at the TPP.

The performed assessment of the investment and production activities of the energy-chemical holding, which combines atomic and thermal ammonia power plants, and the chemical production of ammonia gives an idea of the economic and technological efficiency of the economic complex. It should be a very large capital investment and energy-intensive structure. The project to build an energy-chemical plant with a capacity of 600 kt of ecological ammonia is the first in Denmark and has the status of "Europe's largest green ammonia plant" [22]. For supplying the ammonium fuel to a thermal power plant on the scale of Prydniprovska TPP, which is not the most powerful by Ukrainian standards, in the optimal mode, about 2.7 such enterprises are needed with total capital investments of about 3,800 MEUR (two chemical plants worth 2,800 MEUR are assumed).

Within the holding, not coal, but water becomes a real "fuel"—to produce 1 t of hydrogen, you need to have 9 t of pre-treated water of a high level of purity, for 1 t of ammonia there is almost 1.6 t of water [22]. The problem of water supply, especially in the locations of TPPs in Ukraine, is no less acute than the global problem of combating climate change. A positive aspect of the electrolysis method of obtaining hydrogen is that 8 t of oxygen is released for 1 t of hydrogen, which can be fully used for the effective combustion of ammonia by chemical reaction [23].

Figure 4.
Dependence of the price of electricity, which ensures the break-even operation of the holding in accordance with the cost/price ratio for the TPP.

$$4NH_3 + 3O_2 = 2N_2 + 6H_2O. \tag{12}$$

The combustion of ammonia in air is a difficult process due to the low laminar burning velocity (0.07 m/s) [8] and great problems with ignition of the air-ammonia mixture [8, 23, 24]. Oxygen combustion of ammonia gives a much higher laminar burning velocities [23, 25].

The electricity prices that satisfy the holding's break-even condition depend nonlinearly on the cost of electricity production. Even with very efficient management, the price of electricity should be more than 160 EUR/MWh, which is unattainable for the current conditions of Ukraine, although acceptable for EU countries. Thus, in September 2022, the day-ahead base load price of the Ukrainian market was 90–91 EUR/MWh, while on the Romanian market from September 19 to 24, the average base load price was 366.4 EUR/MWh, and the market of Slovakia—359.5 EUR/MWh, and a week earlier—386.8 and 442.6 EUR/MWh, respectively [26]. The production functions of European TPPs in terms of fuel consumption should be more efficient than Ukrainian ones, because for 1 kWh of electricity supplied to the network, they consume 280–300 g of coal equivalent and operate in base load mode, unlike Ukrainian TPPs that operate in maneuverable modes and consume 400 g/kWh [27].

This chapter does not take into account the possibility of using thermal energy produced in the process of ammonia production to meet the needs of consumers adjacent to the plant. The plant planned to be built in Denmark is capable of solving the problem of heating and hot water supply for 15,000 households in the Esbjerg/Varde area [22]. This remains a powerful resource for increasing the economic efficiency of the processes of switching to ammonium fuel.

Ukraine has no experience in decommissioning coal-fired thermal power plants, but according to US data, the cost of decommissioning a typical 500 MW coal-fired thermal power plant is up to MUSD 1.15 (USD 30 per 1 kW of installed capacity), excluding the cost of scrap metal. As a rule, the term of liquidation is from 18 to 30 months [28]. But the costs can be significantly higher due to the desire of governments to compensate for the negative social consequences. In Germany, for example, to accelerate the closure of coal-fired power plants, tenders were announced for the liquidation of 5.5 GW of generating capacity: closure of 4.0 GW in 2020 with a maximum compensation of 165 EUR/kW; and in 2021, the closing of 1.5 GW of capacity—up to 155 EUR/kW [29].

The electrolytic synthesis of "green" NH_3 is a less energy-consuming process—7.5–8.0 kWh/kg of ammonia [30, 31] than the traditional Haber-Bosch technology. The electrochemical method of ammonia production is widely studied and developed by many researchers [32–35]. Unlike old technologies, which are the same Haber-Bosch method, the physic-chemical processes of the new method will take place at lower temperature parameters and at lower pressure indicators, which can radically change the economic and commercial aspects of the holding's operation.

The problems related to high prices concern only the part of the energy and chemical holding those deals with the production of secondary electricity. However, this does not apply to the holding's ability to operate on the markets of chemical products: nitric acid, nitrogen fertilizers, etc. A chemical plant as part of a vertically integrated system, if ammonia is not supplied to the power plant, and can produce and sell ammonium nitrate at a price of 733 USD/t annually with high profitability [36]. The created energy and chemical holdings have the opportunity to expand their product line—not only electricity, but also nitric acid, fertilizers, hydrogen.

4. Conclusions

The requirements of the green transition of the world's power industry can lead to the elimination of coal-fired thermal power plants as such. The subject of the research is the phenomenon of the circular economy of vertically integrated production systems. The object of research is the economic efficiency of a hypothetical investment project to create an energy-chemical holding combining nuclear and ammonium thermal power plants. As an example, the Ukrainian coal-fired thermal power plant—Prydniprovska TPP was used. This chapter is based on the hypothesis that the use of circular economy techniques in the financial and energy-intensive electrolytic production of "yellow" ammonia will contribute to the break-even operation of environmentally friendly reformed coal-fired thermal power plants.

The originality of the idea is given by the definition of electricity produced by nuclear power plants, but not used due to lack of demand, as a waste that can be recycled with the use of electrolyzers. The recycling of electricity waste as an element of the circular economy and the vertically integrated structure of the energy-chemical holding make it possible to obtain electricity almost free of charge and turn it into cheap ammonium fuel for thermal power plants.

The evaluation of the economic efficiency of the investment project for the creation of an energy-chemical holding was carried out using the NPV (Net Present Value) method: The annual cash flow from the operation of the holding, the value of which depends on the price of electricity and the cost of its production, is compared with the break-even annuity, the value of which depends on the size of capital investments of the cost of capital (discount rate) and the duration of the project.

The model for the calculations is based on the production functions of Prydniprovska TPP, calculating according to the data of many years of observations—the real dependence of the electricity released into the network on the consumption of coal and the calculated one, which is modified for combustion of ammonia. Because of the lower energy parameters of ammonia, the boilers of the power plant have to burn larger volumes of fuel, but at the same time there will be no costs for cleaning the flue gas from dust and sulfur dioxide.

Today, in Denmark, we are talking about the implementation in the near future of the project "Europe's largest green ammonia plant" with a productivity of 600 kt of liquid "green" ammonia per year, the construction of which requires 1,400 MEUR. In order to ensure the functioning of the Prydniprovska TPP, which is not the most powerful in Ukraine, in optimal fuel consumption mode, almost three such plants are needed.

The dependence of the price of electricity produced by the power plant on the cost of operation of the energy-generating enterprise under the conditions of break-even operation of the energy-chemical holding as a whole was obtained. Even with a very economically efficient operation of the thermal power plant, the price of the generated electricity should exceed 160 EUR/MWh, which is currently impossible for Ukraine (at a price of approximately 90 EUR/MWh), although the assessment did not take into account the possibility of utilizing large amounts of thermal energy.

The effectiveness of energy and chemical holdings based on the principles of the circular economy and in Ukraine is now not in doubt if they produce not secondary electricity, but chemical products—NH_3, nitric acid, nitrogen fertilizers, that is, a vertically integrated nuclear power plant and a chemical plant.

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Conflict of interest

The authors declare no conflict of interest.

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Chapter 3

Water Chemistry in Nuclear Power Plant

Md. Nur Salam and Md. Rokonuzzaman

Abstract

Water quality has long been an important part of the operation of nuclear power plants. Water is used as a working and cooling fluid in power plants. The quality of source waters to be used in the power plants after treatment should conform to the prescribed values of Physicochemical properties like pH, EC, TDS, alkalinity, hardness, presence of chloride content, silica, and heavy metals as recommended by technical guidelines. The Physicochemical properties of water must be recovered the recommended values of the World Health Organization (WHO), United States of Public Health (USPH), and power plant water chemistry guidelines. But the values of raw water are very far from the recommended values of Nuclear Power Plants operation. So, it needs to treat to use in the boilers. Gravitation, Carbon filtration, Ion exchange method, and Reverse Osmosis (RO) are good ways to treat the water before use in power plants. The aim of this chapter is to explore the water chemistry of the source water quality parameters values and those of the recommended values of technical guidelines.

Keywords: nuclear power plant, water chemistry, pressurized water reactor, VVER-1200, steam generator

1. Introduction

Vapor and water are used as heat transmission fluids in a number of heat transportation systems, both as a coolant and for heating, because of their accessibility and high heat capacity. A lake or the sea are two potential natural sources of chilly water [1–5]. Because of the high heat of vaporization, condensing steam is a highly effective heating fluid. Water and steam are corrosive, which is a drawback. Water is the coolant in practically all electric power plants, where it makes steam, and the steam spin the turbines that turn generators. Water is used extensively in the US to cool power plants. Water may also be utilized as a neutron moderator in nuclear power plants. Water serves as a condenser and a controller in most nuclear reactors. Removing water from the reactor inhibits the nuclear process.; nonetheless, alternative means for preventing a fission reaction are preferred, and it is preferable to have the nuclear reactor core roofed with water to provide sufficient cooling.

1.1 Water utilization in electric power generation

Thermoelectric or "thermal" power plants boil water to generate steam, which is then used to generate electricity. Hydropower plants, which employ dams and other methods to create energy in moving water, rely heavily on water. The flowing water drives the rotating blades, which spin a generator, and mechanical energy is converted into electrical energy by the spinning of turbines [3–13]. Hydroelectric power generates a significant amount of the world's electricity.

1.2 Water chemistry in nuclear power plant

Cooling water: Most of the water is utilized to keep things cold. Vapor is accustomed to spinning the turbines that create electric power in power plants, which boil water to make steam. The steam is then cooled by drawing massive amounts of water from surrounding rivers, lakes, and seas, which is then utilized to generate additional power.

Boiler water: Thermal power plants use boilers to produce pressurized steam, which is used to spin turbines to generate electricity. The theory of the Rankin Cycle does this. To produce a team, every boiler needs a huge amount of fuel. Coal, gas, oil, and nuclear fuel are used to heat boiler water.

Process water: A thermal power production plant that converts heat energy into electricity. A steam-driven turbine transforms heat into mechanical power as an intermediary to electrical power. Water is heated, converted to steam, and then used to drive a steam turbine, which moves a power generator to produce electricity.

Consumptive water: A condenser removes heat from the water cycle in a conventional thermoelectric power plant. Cooling water is utilized to get rid of the heat. The USGS (United States Geological Survey) also measured the quantity of water consumed by thermoelectric power plants (amount of water evaporated, transpired, or absorbed into products).

1.3 The layout of nuclear power plant

There is various equipment used in a nuclear power plant. The most important parts are:

a. Fuel rod (Uranium is the basic fuel).

b. Blades/ Control rods.

c. Moderator /coolant.

d. Reactor pressure vessel.

e. Steam/vapor Generator

f. Turbine/generator

g. Containment

In steam turbines and steam turbine generators, superheaters are commonly utilized (HRSGs). Their goal is to elevate the temperature from saturation to the appropriate ultimate temperature, which in certain situations can be as high as 1000°F. When utilized in steam turbines, superheated steam lowers the turbine's heat rate and, as a result, lowers the turbine's steam heat rate, improving the turbine and related to plant power and output efficiency. Also, based on the pressure ratio, steam situations at the steam turbine exhaust will have no moisture; nonetheless, moisture in the last few phases of a steam turbine might harm the turbine blades. Some design approaches and performance elements of superheaters that might be of relevance to power station engineers may be found in the study that are listed/mentioned below. The most important components of a nuclear power plant are:

a. Water storage tank

b. Water circulating pump

c. Boiler/steam generator

d. Turbine

e. Generator

In a pressurized water reactor (PWR), a nuclear power plant contains three main circuits:

- The primary circuit absorbs heat from the reactor core and transfers it to the secondary to produce steam.

- In this circuit, the water turns into steam.

- The tertiary circuit is called the cooling circuit. Here the steam condenses and turns into water (**Figure 1**).

1.3.1 Primary circuit

PWRs are a type of pressurized water reactor that uses ordinary water as a controller and coolant. A main cooling circuit that runs under tremendous pressure through the reactor core and a secondary circuit that creates steam to power the turbine define the architecture [15–17]. The heat from the reactor's fuel rods was transported to a primary circuit that held water. This water gets incredibly hot (about 300°C), yet it does not boil since it's kept under pressure (around 155 bar). As a result, the moniker "pressurized water reactor" was coined [14].

1.3.2 Secondary circuit

The water in the secondary circuit is at reduced pressure, so it blooms in the heat transfer, which acts as a steam/vapor generator. The vapor is condensed and transferred to the heat transfer in connection with the previous (primary) circuit then it drives the turbine and produces energy. The steam generator receives the heated water via a heat exchanger. Heat is transmitted from the reactor cooling water to a different secondary circuit (the steam-water circuit). Water is transformed to steam in

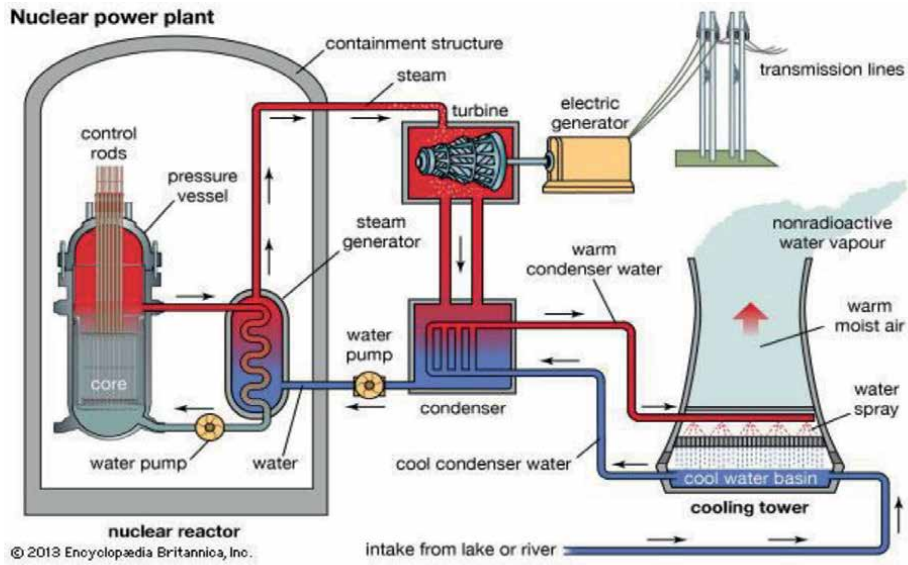

Figure 1.
Layout of nuclear power plant [14].

this circuit due to the reduced pressure; the vapor is then utilized to turn the turbine linked to a generator [14].

1.3.3 Tertiary circuit

At last, the steam that exits the turbine is cooled and turned back into the water. The condenser is cooled using a different tertiary cooling circuit that uses water from an external device [14].

2. Methodology

Water quality from diverse sources was studied and compared to the standard value of boiler water from a typical thermal power plant and the secondary circuit of the VVER-1200 PWR Reactor. To determine pH a digital pH meter (Model HT 2002-0, S/N CO316002, Hanna instrument) was utilized. The chemical properties of the water samples were determined using various analytical tests and a digital EC and TDS meter (Model S/N: Co127A, Hanna-2003-02). Heavy metals were also investigated using the Atomic Absorption Spectrophotometric (AAS) process, and the chemical properties (Hardness, Alkalinity, Chloride, and Silica) of the water samples were determined using various analytical tests.

2.1 Water purification method in power plant

This chapter briefly describes all experimental observations that are presented in the form of numerical data relevant to the individual samples used in the current experiments. It is representing the study on the analysis of water quality of the source waters and the recommended value of boiler water of Nuclear Power Plant and

No	Parameter	Unit	Recommended values of PWR secondary circuit
1	pH		4.5–10
2	Electrical conductivity (EC) at 25°C	μS/cm	00
3	TDS	ppm	00
4	Chloride	ppm	<0.1
5	Total hardness	ppm	00
6	Total alkalinity	ppm	00
7	Silica (SiO_2)	ppm	—

Table 1.
Recommended values of water quality for PWR secondary circuit.

secondary circuit of VVER-1200 PWR reactor. The deviations between the obtained values and the recommended values are briefly discussed in the following section. Before and after treatment, several water quality parameters such as pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS), Chloride, Total Hardness (TA), Total Alkalinity (TA), Silica (SiO_2), and Heavy Metals were meticulously monitored. Then, to utilize for power generation, we picked the optimal condition of the best quality of source waters (**Table 1**).

2.1.1 Distillation

Distillation has several advantages. The technology is relatively affordable, except for glassware and warming components, there are no extra costs, and it generates water of generally acceptable quality. The water of Type II or III quality is commonly produced by distillation, with a resistivity of around 1.0 mega-ohm/cm. However, distillation has several disadvantages, and as a result, it is not as commonly employed as it once was. Distillation is not just a process that can be done whenever you want it. As a result of this, a certain amount of water must be purified and saved for future use. Charge particles or plasticizers will filter outside of the water pot if the storage vessel is not composed of an inert substance, decontaminating the water. Bacteria have been shown to thrive in stagnant water. The water sample was autoclaved, and the bottles could be sterilized. The bottle, however, is exposed to microorganisms once it is opened, and contamination occurs. Distillation has other disadvantages, such as wasting a lot of water and energy. It must be cleaned regularly since mineral deposits from the feedwater have built up.

2.1.2 Deionization

In laboratories, deionization is a common procedure for producing distilled water on demand. Most deionization systems consist of one-to-four-cylinder cartridges linked to plumbing lines and hanging on a wall opposite a sink. Deionization exchanges hydrogen ions for cationic pollutants and hydroxyl ions for anion exchange impurities in the input water. The desalination resins, which are little spherical plastic beads, filter the feed water. Over time, water cations and anions replace all of the fertile hydrogen and hydroxyl groups in the seeds, necessitating the replacement or regeneration of the resin. Deionization has several advantages when it comes to producing clean water (over distillation). Because it is an on-demand technique, purified water may be delivered on demand. Nuclear standard desalination resin or polishing mixed bed resin eliminates virtually all ionic particles in water to a maximum resistance of 18.2 mega ohm/cm (at 25°C). Deionization, on the other hand, does not ensure that the water is completely free of contaminants. Small particles of ion exchange resin are pushed out of the system during operation, and stagnant water in the cartridges may encourage bacterial development. Deionization does not remove all dissolved organic molecules from the feedwater, and these chemicals might foul the ionic liquid.

Finally, for laboratories that want to replace rather than regenerate their deionization cartridges, deionization cartridges might be a costly choice. Many attempts have been made to address the drawbacks of deionization and distilled. The cartridges survive significantly longer in some configurations where distillation precedes deionization, but the concerns of bacterial contamination persist [15].

2.1.3 Reverse osmosis

Reverse osmosis is a water purification technique that avoids many of the disadvantages of distillation and deionization. The natural mechanism of osmosis may be used to explain reverse osmosis. Osmosis is the process of water moving from the less concentrated (purer) side of a semipermeable membrane to the more saturated (saltier) side [18–20]. This movement continues until the concentrations reach equilibrium, or until the pressure on the more concentrated side rises to the point where the flow is halted. Osmosis, which is also the natural technique by which water travels from one cell to another in human bodies, is used to get water into a plant's root. When a high-pressure pump is used to apply pressure to the more concentrated solution that is greater than the osmotic pressure, water molecules are driven back over the membrane to the less concentrated side, resulting in purified water. This is an example of reverse osmosis in operation. Most pollutants are normally removed by reverse osmosis, which eliminates 90–99% of them [2].

Table 2 shows the technical specifications of reverse osmosis.

Reverse osmosis is a cost-effective technology that is widely used in fresh tap water before it is cleansed further using other technologies due to its high purification efficacy. Reverse osmosis is widely used in combination with the ion exchange process

Impurities	Extraction efficiency (%)
Dissolved solids	100
Bacteria	99.5
Pyrogens	99.5
Viruses	99.5
Monovalent inorganics	94–96
Divalent inorganics	96–98
Trivalent inorganics	98–99
Organic substances	97–99.5

Table 2.
Performance of reverse osmosis [2].

to increase the life of deionization "polishing" cartridges since it removes a substantial percentage of bacteria and pyrogens. Furthermore, a system that allows for the dispensing of reverse osmosis water provides a source of high-quality pre-purified water that is suitable for several laboratory applications.

2.1.4 Activated carbon filtration

Activated carbon filtration, which uses strong interaction and desorption to remove chlorine and soluble organic substances from water, is frequently found in two regions of a purifier. Even though chlorine and, to a smaller extent, dissolved organics contaminate thin-film composite reverse osmosis membranes, activated carbon is commonly utilized before the Ro system to remove these contaminants. In the polishing loop of a water purifier, a solid activated carbon filter is typically utilized to extract trace quantities of dissolved organics, resulting in water suitable for HPLC tests.

2.1.5 Ultrafiltration

Ultrafiltration employs a membrane that is essentially represented by RO systems, with the exception that the holes in the ultrafilter are somewhat bigger. Pyrogens and other big-chain biological substances or organic compounds such as RNase are removed from cleaned water using an ultrafilter. Because a large portion of the water delivered to the ultrafilter travels through it, if it is not maintained, it will ultimately block. The ultrafilter is routinely and tangentially cleansed free of impurities in a suitably constructed system. Ultrafiltration is an excellent technique for assuring highly consistent, very clean water quality with this sort of construction.

2.1.6 Ultraviolet oxidation

Ultraviolet oxidation kills bacteria by emitting ultraviolet light with a biocidal wavelength of 254 nm. It also split and ionizes some organics at 185 (nm), which are then removed by the polishing loop's deionization and organic adsorption cartridges. In modern water purification techniques, ultrafiltration is widely used for drinking water.

2.1.7 Electrodialysis

Electrodialysis (ED) eliminates pollutants from water by drawing charging contaminates via charge-selective membranes and out of the cleaned water using an electrical current. ED is cost comparable with reverse osmosis for producing potable water from fresh brackish source water. However, ED has several disadvantages when it comes to producing laboratory-grade water, and as a result, it is rarely employed in labs. To begin with, ED's ability to remove pollutants is restricted. Because they are not driven to the membranes, pollutants with weak or nonexistent charge density, such as some organics, pyrogens, and elemental metals, cannot be removed by ED [21–25]. Second, ED necessitates the use of a professional operator as well as frequent protection. Greater molecules with a substantial charge, such as colloids and detergents, can clog membrane pores, limiting their capacity to transport ions and necessitating regular cleaning. ED releases caustic soda, which can cause scaling, as well as potentially hazardous hydrogen gas. Finally, ED is a somewhat costly procedure.

The electrical resistance of water rises as ionic pollutants are eliminated, requiring a greater electrical current to complete the purification process. Because of the higher power usage, purification above the potable level is considered uneconomical. Platinum and stainless steel, for example, are both costly component materials [2].

3. Conclusion

Water quality has long been an important factor in nuclear power plant (NPP) operation A proper water chemistry program is important for the safe operation of power plants. It ensures the integrity, reliability, and availability of the main plant structures, systems, and equipment that are essential for safety, by the assumptions and intentions of the design. Water is used as a working and cooling fluid in power plants. The chemistry of water coolants and corrosion concerns is particularly important in nuclear power plants. As a result, a water regime for commercially water-cooled equipment must be created to prescribe the values of water quality parameters such as Turbidity, pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS), Total Hardness, Alkalinity, Chloride Content, Silica, and Heavy Metals. Hence, this chapter has been undertaken to study the water characteristics of nuclear power plants.

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Chapter 4

Perspective Chapter: Efficiency of the Phased Financing of the Construction of a Nuclear Energy System with Small Reactors

Vladimir Usanov and Stepan Kviatkovskii

Abstract

The chapter is directed to finding ways to enhancing investment attractiveness of small and medium reactors (SMRs). The approach being discussed in the chapter is based on the notion that mechanisms for financing a power system can be more flexible and efficient than those used to finance individual units. As an implementation of this general idea, a matrix investment model, in which management and financing are centralized, is presented and discussed. Results of the model application for evaluation of the economic indicators of SMR system construction are compared with the results provided by the levelized cost model. The results of the comparison show that integration of few SMRs into a financially united system opens up opportunities for the shareholder income growth, creates favorable conditions for credit/private investors and promote public acceptance of nuclear power as a cost-effective energy option.

Keywords: nuclear power, electricity generation, levelized unit electricity cost, economic efficiency, small and modular reactors

1. Introduction

The comprehensive research of recent decades shows a significant role that nuclear power can play (and is already playing today) in reducing greenhouse gas emissions and preserving the environment, while ensuring a sustainable energy supply [1–6]. The growing recognition of the objective capabilities of the nuclear energy option in preventing climate change and reducing of the environmental impact is a critical condition for the inclusion of nuclear power into the energy sector of many countries, which, however, does not guarantee its large-scale deployment without solving some internal problems.

One of these problems is low return on investment in nuclear energy business. For a long time, when the main type of electricity markets was a regulated one, financing of the power plants was provided by state or municipal structures, with preference given to reducing electricity prices as a social task, rather than electricity generation as a business. The low electricity price was being achieved by investing in the NPP construction low cost capital provided by the state or municipal corporations with a very long-term return. These favorable financial conditions made it possible to build power units of high capacity over a long period of time in order to rich lower cost of electricity than one in units of smaller capacity due to economies of unit scale (scale effect).

Under funding conditions similar to the mentioned above, large generation reactor units occupied a significant place in the world nuclear power generation, maintaining to a large extent the development trend in the same direction. In contrast to the specific nuclear power market, the deregulated non-nuclear power markets have evolved away from the very large generation units toward small and medium ones. The intrinsic complexity, associated risks and costs of extremely large systems have offset all economies of unit scale in power engineering [7]. Since the end of the last century, interest to small and medium reactors has also been rapidly growing in the nuclear power. By now, more than a hundred of SMR designs have been developed in the world and some of them are in the implementation phase [8–10]. Increased design activities on SMRs were driven by new opportunities offered by this technology: inherent safety; adaptability to mass fabrication, facilitated transportation and localization in remote regions; flexibility; possibility of integration with renewables; adaptability to small power grids, etc. SMRs also have a number of economic advantages compared to high power reactors (HPRs): lower total capital investments in the construction of a power unit, shorter times for commissioning, lower capital value at risk during construction, significantly lower amount of civil liability insurance.

Although in many respects SMRs are close to those of small and medium non-nuclear power units, there is a significant difference that adversely affects the deployment of a nuclear option of this type. The problem is the high overnight capital cost of the SMR building, which leads to exclusion of credit financing, high electricity costs, and, ultimately, low return on capital. The chapter evaluates an opportunity for enhancing investment attractiveness of SMRs by creating on their basis a net commercial structure—a financially integrated energy system.

2. Economic grounds for uniting power units in a financially integrated system

2.1 Specific features of nuclear power units financing

In the studies on the comparative assessment of the economic efficiency of power plants of various types in scenarios for the development of the energy sector of countries and regions, the levelized costs of electricity (LCOE) method is commonly used [11, 12]. The constant value of the specific cost of production of one kWh of electricity, being determined in this method, provides the same net present value of the electricity unit as the time-distributed income and expense flows associated with the life-time operation of the facility. Being very useful in general assessments, the LCOE model does not take into account many factors that affect the real cost of electricity, such as specific regional conditions, the number of power units on the site, infrastructure, specific ways of financing, etc. All these factors remain outside the scope of consideration in forecasting cost. For the study discussed in the chapter, it is essential that the LCOE method offers an overly simplistic approach to estimating the cost of capital and does not distinguish between the cost of electricity generated by the one power unit and a system of several units. Theoretical analysis provided below makes it possible to understand why the LCOE model does not correctly describe the process of investing in energy projects for two main mechanisms of financing: from equity and bank capital.

The levelized unit electricity cost c of electricity is the sum of the component r for the recovery of capital invested in the construction of the power unit and the component of operating costs u, which includes fuel costs. The focus of the chapter is the component r of the reimbursement of the investments K made in the power unit construction. Assuming that unit operating costs u and power unit q generation remain constant during the period of the power unit operation, an equation for c can be presented as:

$$c = r + u = \frac{K \bullet i}{q \bullet (1 - e^{-iT})} + u, \tag{1}$$

where i—weighted average cost of capital WACC; q—annual electricity unit production; T—repayment period.

The equation for calculation of investments (total cost of construction) K is:

$$K = \int_{-T_c}^{0} k_t e^{-it} dt \tag{2}$$

where k_t—investment in time from the start of construction of the power unit $t = -Tc$ to the start of the unit operation $t = 0$.

The cost of capital i is a key value for assessing the investment project profitability by bringing cash flows at different points in time to a single reference point and choosing the most promising investment from the available ones. It generally characterizes the investment climate in a country while sometimes serves as an element of technical policy, creating preferential conditions for a particular energy technology. In the case when the project is supposed to be invested by equity holders and debt, money i is usually defined as the weighted average cost of capital (WACC):

$$i = \varepsilon_D \cdot i_D + \varepsilon_E \cdot i_E, \tag{3}$$

ε_D, ε_E—shares of debt and equity, respectively ($\varepsilon_D + \varepsilon_E = 1$); i_D , i_E—interest on debt and equity.

The weighted average cost of capital partly reflects the fact that investment sources are inherently different. In particular, shareholders bear a much greater risk than creditors, so the return on equity should be higher than on debt, which can be taken into account using Eq. (3). However, a simple "weighing" of interest on debt and equity does not provide a correct guideline for choosing a project investment strategy from internal and external financial sources. Eq. (3) does not describe the distribution of investment and return flows of owners and creditors over time, which significantly affect the results of cost calculations. The owners (shareholders) return their funds with dividends during the commercial operation of the power plant over a period of 30–60 years, while the typical time to repay debt to creditors (banks and investment funds) is much shorter: 5–15 years. These features determine the choice of investment model for energy sources of various types. The Eq. (1) implies some asymptotic (limit) relations for the component r, which determine possible value of return in different circumstances:

$$r_0 \approx \frac{K}{q \bullet T}, \textit{ when } \mathrm{T} \to \infty, iT \to \infty, e^{-iT} \approx 0; \tag{4}$$

$$r_E \approx \frac{K \bullet i}{q}, \textit{ when } i \approx 0, iT \approx 0, e^{-iT} \approx 1 - iT; \tag{5}$$

$$r_D \approx \frac{K \bullet i}{q \bullet \mu} \gg \frac{K \bullet i}{q}, \textit{ when } \mathrm{T} \to 0, iT \to 0, \mu = 1 - e^{-iT} \ll 1. \tag{6}$$

Eq. (4) corresponds to the case of the power unit building by the state or a municipal company with very low interest rate on invested capital and the time of the investment return T equal or comparable to the lifetime of the unit T_0. In this case, the value of the funds K invested in the unit construction is close to the value of overnight cost K_0. The annual return on investments is the lowest among practically possible. This option, as noted in the introduction, is a part of socially oriented energy policy directed to provide low prices for customers. At the same time, it puts the big players on the verge of economic survival and closes the door for all other potential investors.

The limit relation (5) describes a quite widespread practice of power units financing by shareholders and creditors that is more profitable for investors (primarily under high WACC) than that in the case described by the ratio (4). However, for nuclear power where K value is much higher than in non-nuclear units, the only way to implement relation (5) and get acceptable unit electricity cost is to decrease the component r in Eq. (1) by fulfilling the condition

$$e^{-i_E T_E} \approx 0, \tag{7}$$

which, in turn, can be performed with a long return on investment. Therefore, in nuclear power, the scheme (5) for investment return is being mainly used by shareholders who, as owners, are quite satisfied with receiving dividends on invested capital for a long time. It should be noted that the amount of nominal money r_E being returned annually to shareholders according to scheme (5) can many times exceed the amount of money r_0 to be returned annually according to scheme (4) for a simple refurbishment of equity capital K invested in the construction of a nuclear power unit:

$$\frac{r_E}{r_0} \approx i_E \bullet T_E. \tag{8}$$

The situation of short-term return of money by creditors is described by the limit relation (6). Due to the fact that μ in (6) at $\mathrm{T} \to 0$ becomes very small, the amount of funds annually returned to creditors r_D tends to grow rapidly. For the energy technologies with a low share of the investment component in the cost of electricity, such as CCGT, an increase in the r_D component does not significantly affect the cost of electricity.

The situation is different for energy technologies with a high share of the investment return component in the structure of electricity cost, to which applies nuclear power. Attraction of credit money, the annual return on which per invested unit is much higher than on equity capital, means a radical increase in the cost of electricity generated during period of the credit repayment T_D and significant problems for entering the competitive market. Thus, for energy technologies with a high share of the investment component in the cost of electricity, short-term credit money is not attractive, and NPP owners—large state or private companies—usually do not apply to them. The problems related to the use of credit money in nuclear power were clearly demonstrated in [13]. To mitigate the harmful effect of short-term credit money, it was suggested in [13] to reduce the amount of return to shareholders during the credit repayment time with compensation of the losses incurred by shareholders after full return of money to creditors. This approach has reduced the cost of electricity in the variant of comparable shares of credit and equity investments, but the need to compensate to the shareholders losses with money depreciating over time, ultimately has led to higher levelized cost of electricity than in the case of only equity investment.

Thus, some features of nuclear energy lead to the formation of a rather narrow range of potential investors interested in the development of the nuclear energy business. There is an existential necessity in significant expansion of this range in order to meet the requests from existing energy markets on the reduction of the unit capacity of power units and the increase in commercial attractiveness of their building. In achieving this objective, all available technical, technological and institutional opportunities should be used. The chapter deals with the issues of improving institutional mechanisms embodying actualizing a transition from the scale of a power unit to the scale of a unit system with enhanced investment attractiveness. The chapter shows that an effective instrument for such a transition can be organization of a matrix cash flow capable to meet interests of stakeholders and creditors better than the linear one of the levelized cost model.

2.2 Cash flow matrix model

It was shown in [14] that the cost-forming mechanisms in an electricity generating system of several power units may differ from those of an individual unit. Under certain conditions, the cost of electricity produced by a power system can be lower than the cost of electricity generated by a unit. The general idea is to distribute the financial burden that falls on a separate power unit spread over multiple units of a high capacity system. It is possible by combining independent units into an economically connected cluster—a structure with centralized management, including the management of joint finances. Investment can be made on the basis of a phased approach in accordance with the plan of power units construction. The fundamental importance for such a system is the separation of investments with a short-term return (credits and accelerated equity return) and a long-term return of the main shareholders' equity capital.

Figure 1 shows the scheme of investment and return of funds by investors in a financially integrated system adopted for this study. To simplify the analysis of the system cost of generated electricity, it is assumed that the construction of a new power unit of a cluster begins when the credit money invested in the construction of the previous unit has been paid.

In the case of sequential commissioning of power units in accordance with the adopted scheme, the value of the unit system cost of electricity c_N generated by the system with N units in the financially connected cluster will be equal to:

$$c_N = \frac{\varepsilon_{DN} \bullet K_D \bullet i_D}{N \bullet q \bullet (1 - e^{-i_D T_D})} + \frac{K_E \bullet i_E}{q \bullet (1 - e^{-i_E T_E})} \sum_{n=1}^{N} (1 - \varepsilon_{Dn}) \qquad (9)$$

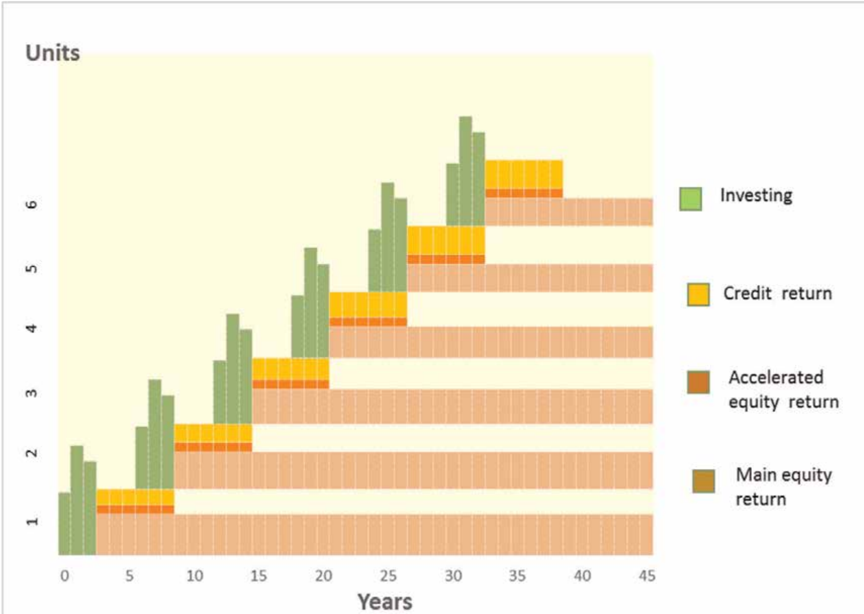

Figure 1.
Network cash flow in the financially integrated system.

where ε_{Dn}—the share of short-term money for the unit n (n = 1, 2, … , N); K_E—investment of shareholders (long-term money); K_D—investment of creditors & shareholders (short-term money); i_D—interest on credit and equity capital; T_D, T_E—times for short-term and long-term return.

The systemic effect of reducing the unit cost of electricity in a cluster occurs when $N > 1$ determined by several circumstances. The main thing is that in accordance with assumptions made above the repayment of the short-term investments for the construction of power units with the numbers less than N has been completed. Therefore, the repayment on the short-term investments to be made for the unit N should be attributed not to the electricity production of one unit but to the electricity production of the entire system of N power units. Then the component r related to the contribution of the short-term return on investment to the electricity cost generated by the power unit number N in the system will decrease by N times comparing to the short-term component r of the electricity cost generated by a single power unit of the same type.

To enhance the effect of short-term return on investment in decreasing the electricity cost due to the mechanism described by Eq. (9), the partial accelerated return of shareholder investment can also be implied. The share of this accelerated return should be carefully verified, as well as debt return, proceeding from the level of the system deployment and the interests of shareholders.

The component of the long-term return to shareholders is represented by the right part of the Eq. (9). It consists of the repayments for all N units of the system when the time of the system building is less than the period for the return of funds to the shareholders. Since the amount of money to be returned to shareholders, as well as the amount of electricity produced by the system, is proportional to the number of power units in the system, there is no explicit dependence of the long-term return on N, in contrast to the short-term return. However, it as follows from the Eq. (9) the return to the shareholders for the system is also less then long-term return of *N* units not united in financially integrated system due to the gradual replacement the investments with a long-term return by the investments with a short-term return. To carry out calculations of the electricity cost based on Eq. (9), a matrix cash flow model capable to take into account input of nuclear capacities at different times was developed. A flexible cash flow managing in the matrix model of the financially integrated system with a linear cash flow for each power unit and flows of money between the units provides an opportunity to improve efficiency of the equity capital use and, ultimately, increase the shareholders income.

3. Evaluation of economic indicators of the financially integrated system with SMRs

3.1 Rationale for the selection of SMRs as basic power units of the united system

Generally speaking, the synergetic effect arising from the managerial and financial integration of power units into a united system in accordance with the mechanism described by Eq. (9), is universal and occurs both for nuclear and non-nuclear power units of different capacities. However, due to the specific features of power units with a very high share of overnight cost and investment in the electricity cost like wind, solar and nuclear, the managerial and financial integration of the units into a system appears to be most effective, especially in case of small capacities. In nuclear, these types of units are SMRs. Nowadays, there are a lot of research on pros and cons of this direction of nuclear power development. Some SMRs' features may be put forward as especially important for the building of a holistic system:

- comparatively low initial investment in the construction of a small pilot power unit of a projected system of desired capacity makes feasible launching up of such a system with less financial and infrastructural efforts than launching up a system with a pilot power unit of large capacity;

- manufacturing and assembling main equipment of the SMRs at the factory can provide an opportunity for the short-term debt return due to radically decreasing the time for the equipment fabrication, power units and the whole system commissioning and transportation of the assembled units to the deployment site;

- phased construction of the small power units allows shareholders to adjust the capacity input to the pace of economic development and the growth of electricity consumption in the country or region;

- mass fabrication of small reactors should lead to an increase in the scale of production and income of the industry;

- new business direction with more flexible possibilities for input and return of money may attract a wide spectrum of public and private capital.

The concept of a financially integrated system does not imply the mandatory installation of power units on the same site. An effective strategic planning, financing and coordination can be carried out from one management center while the elements of the system can be geographically distributed.

3.2 Technical and economic characteristics of SMRs

To date, dozens of SMRs projects have been developed in the world, differing in purpose, capacity and neutron spectrum, type of coolant, design and stage of development. **Table 1** shows the technical and economic characteristics of a power reactor used in test calculations of the matrix model. The capacity of the reactor is in the upper part of the power range for small reactors. The data were selected based on the analysis of publications on a large number of SMRs projects [7–10]. The mastered technology of pressurized water reactors which probably will form a first generation of SMRs in the near future served as a reference of a basic power unit for testing a model of a financially integrated system.

The choice of financial data for carrying out test calculations of the financially integrated model is associated with a number of specific features of this model and the general formulation of the problem. There are possibilities for various combinations of financing options from the shareholders and credit institutions with different values of interest and conditions for money return period. A part of the financial data and the variation range of discount rate and equity rate of return used in the test calculations are shown in **Table 2**.

3.3 Cost-income model

Due to many degrees of freedom for selection of fractions shareholder and creditor investments and interests on their capital, finding a set of parameters that would provide the best economic performance of the financially integrated system is an extremely difficult task. The values of discount rate (WACC), the debt (credit) rate return, credit repayment period and long-term equity repayment period mainly depend on investment climate in the region of nuclear power building so that their choice is quite a routine. Unlike that, the choice of equity and debt shares, the rate of accelerated equity return defines specific features of the financially integrated system as an object of the competitive environment. The financial parameters should be chosen so as to ensure the stated interests of shareholders and creditors. To confirm

Parameter	Range	Value
Installed capacity, MWe	150–300	300
Load factor, %	80–92	92
Life time, years	40–60	60
Construction time of a power unit, years	2–5	3
Overnight capital cost, $/kWe	1200–5000	4000
Operating and maintenance cost, $/MWh	10–20	12
Fuel cost, $/MWh	4–10	8
Number of power units in the system	5–6	6
Span between unit commissioning, years	—	9

Table 1.
Technical and economic reactors characteristics.

	Model	
Parameter	**LCOE unit**	**Integrated system**
Discount rate in LCOE, %	8–12	
Rate of equity return, %		8–12
Rate of debt return, %		8
Debt repayment period, years		6
Long-term equity repayment, years	60	60
Short-term equity repayment, years		6

Table 2.
Financing conditions.

the methodological consistency of the system model, it also should be shown that the system cost nowhere exceeds the cost of a single power unit.

The concept of investing adopted in the financially integrated system develops a general idea of the approach put forward in [13]. The idea of a more flexible approach to the management of shareholders' capital, as interpreted by the authors of the chapter, is implemented in a matrix model of cash flows [15]. The shareholders' investment return is divided to two parts. The first part is intended to decrease the cost of electricity by making partial returns on shares through payments. The second part is designed to repay to shareholders the difference between the purchase price in the market and decreased cost of electricity generation. The purchase price of the market is taken to be the value of the cost of electricity generated by one unit. Results of this cost-income model application to the test calculations of some economic indicators of the financially integrated system are being discussed in the chapter.

The main cost-cutting mechanisms can be explained by two factors. The first factor is more effective use of money being returned to shareholders since money returned in the short-term period (accelerated shareholder return) is more valuable than ones being returned after a long period of time, when they depreciate heavily. The second factor is the use of credit money which provides a part of electricity generation, while only shareholders receive the full income.

The matrix cash flow model was used for simulation of two scenarios of the system deployment. The shares of equity and debt investing and the rate of return on equity in the test model of the financially integrated system with SMRs for two scenarios of the system deployment are shown in **Table 3**.

The S1S scenario postulates high rates of return on shares (interest on shares in percentages) that can be provided at high electricity selling price, while the S2S scenario postulates lower rates of return at lower selling price of electricity. Various rates of return are adopted in order to explore the possibilities and limits of improving the economic performance of a financially integrated system depending on the price of electricity at the market. As can be seen, the terms of financing in the network model differ not only in the rate of return to shareholders, but also in the timing of return to shareholders as indicated in **Table 2**.

3.4 Electricity cost

Figure 2 illustrates results of calculations of unit cost of electricity generation at values of equity return rates specified in **Table 2**. Straight lines represent results

	Number of power units		1	2	3	4	5	6
S1K	Long-term equity return	Share, %	90	85	76	66	56	46
		Rate, %	9	9	9	10	10	10
	Short-term equity return	Share, %	6	5	4	4	4	4
		Rate, %	12	11	11	8	8	8
	Debt return	Share, %	4	10	20	30	40	50
S2K	Long-term equity return	Share, %	92	86	82	80	77	74
		Rate, %	4	4	4	4	4	4
	Short-termequity return	Share, %	4	6	6	6	6	6
		Rate, %	12	8	8	8	8	8
	Debt return	Share, %	4	10	12	14	17	20

Table 3.
Shares of equity and debt investing and nominal rate of return on equity in the test model of the financially integrated system building.

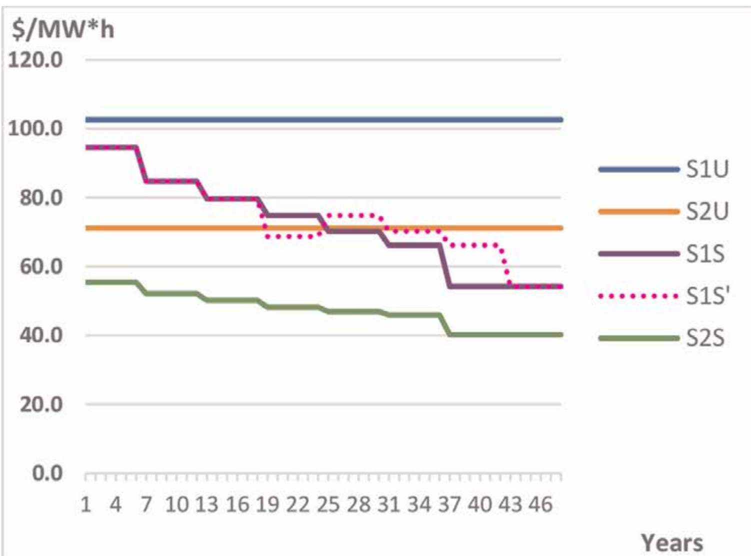

Figure 2.
Unit cost of electricity generation for different scenarios.

obtained with the use of the levelized cost model for one power unit with 12% discount rate (scenario S1U) and 8% discount rate (scenario S2U). These unit costs are compared with the "internal" unit cost of electricity generated by the financially integrated system calculated with the use of the network model with high electricity selling price (scenario S1S) and low electricity selling price (scenarios S2S).

As seen in **Figure 2**, a unit cost of electricity obtained in the test calculation of the financially integrated system with the investing data from **Table 3** is lower than the purchasing price of electricity. The cost reduction correlates with the number of the power units in the system—the more units, the lower the cost.

The short-term return plays the main role in this process. A gradual increasing of the debt money share contributes to the related system costs reducing in accordance with Eq. (9). Another cash flows management tool contributed to the decreasing shapes of the cost curves in **Figure 2** is an accelerated return of equity capital. The shift of a part of the money to be returned to shareholders in a remote period of time, where they lose their value, to the initial period of the system deploy, where the value of money is much higher, proved to be quite effective for reducing the cost of electricity generation in the system.

As follows from **Figure 2**, for the case of shareholder and credit investments and reimbursement rates given in **Table 3**, the relative synergistic effect of reducing cost of electricity in the financial integrating system turns out to be quite close in magnitude at different electricity selling price. The generation cost for a cluster of six units in S1S scenario with high selling price is reduced by 1.9 times compared to the reference cost of electricity for a single unit obtained in S1U scenario. The corresponding decrease in the S2S scenario compared to the reference cost in the S2U scenario is 1.8 times.

A delay in construction of a system after the commissioning of few power units does not lead to significant financial losses for shareholders. As shown in **Figure 2**, a stop in the construction of the system in the C1K' scenario after the commissioning of the third power unit leads at first even to a decrease in the cost of electricity, since investments in further construction are delayed. The obtained economic indicators appeared to be "frozen" at the level that corresponds to the number of units put into operation. With the continuation of the system deployment, the cost of generating electricity will at first increase because of need for new investments and then again will reach the level corresponding to the number of power units in the system.

3.5 Shareholder income

The option for reducing cost of electricity generation during the deployment of the system may be requested for the purpose of increasing the economic competitiveness of the nuclear electricity production. In this case, the values of equity return rates specified in **Table 2** should be kept at the same level. At the same time, if the acceptable cost of electricity in the system is reached (on the first power unit or later) the further reduction of the cost can be used for increasing the income of shareholders by transferring to shareholders the revenue coming from the difference between constant purchase prices in the market and the declining electricity cost generated by the system. The calculations show that increasing of the shareholders income can be significant (**Figure 3**).

With the completion of the system deployment, the initial income can be increased by ∼1.6 times for the S1S scenario and by ∼1.3 times for the S2S scenario. Hence, combining individual units into a system gives an essential economic result. As can be seen, the effect of the income increase can be especially significant in case of high purchase price of electricity. Thus, organization of a financially integrated system with SMRs makes it possible to increase income of the shareholders and provide acceptable conditions for credit capital thus making more attractive the nuclear power business for the financial organization and general public.

3.6 The structure of electricity cost

The main mechanism leading to the growth of shareholders' income in the system is an increase in the efficiency of equity investment—the ratio of the discounted income of shareholders to the amount of their investment in the project. Calculations

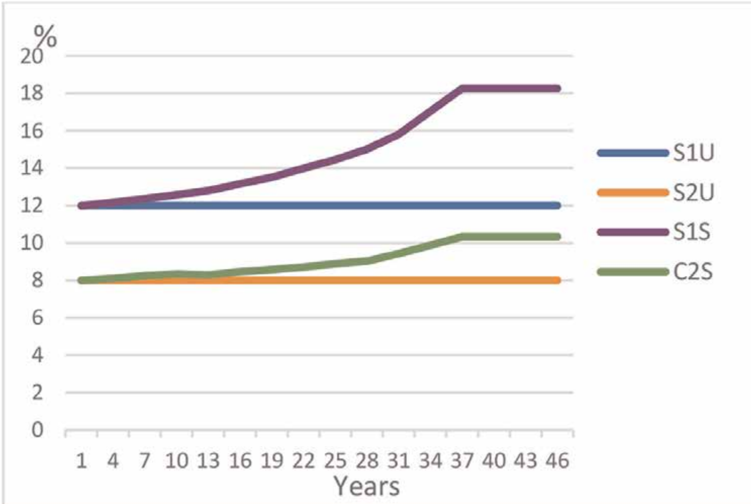

Figure 3.
The shareholder income growth.

show that this indicator is 1.3 for the considered SMR power units not integrated financially in a system. It is about the same for the first unit of the financially integrated system but grows to 5.2 for the sixth unit. A significant increase in the efficiency of equity investment can be explained by reducing the contribution of shareholders to the financing of each new power unit of the system and at the same time increasing their income. Results of calculations of the electricity cost structure for the case of high purchasing price of electricity on the market are illustrated in **Figure 4**.

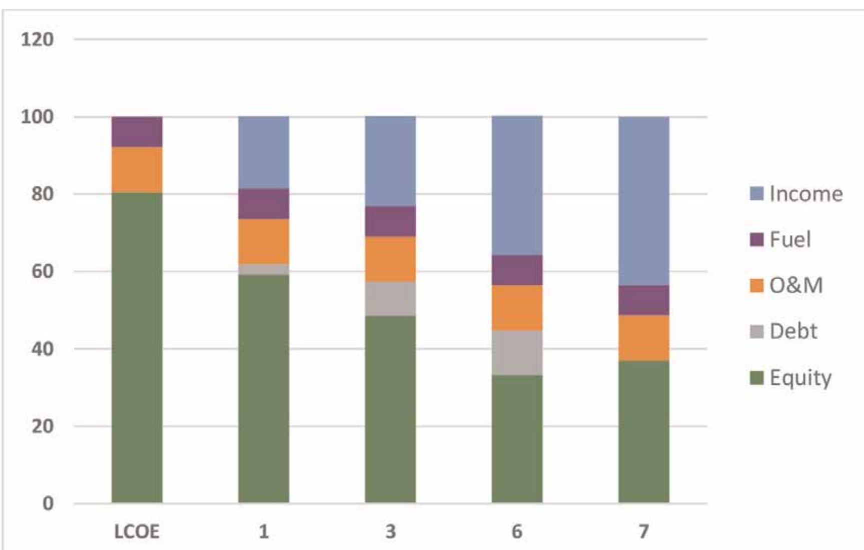

Figure 4.
The structure of electricity cost for the first, third, sixth and seventh power unit of the financially integrated nuclear power system.

As follows from the diagram in the **Figure 4**, the equity share in the cost of electricity generated by one power unit in the S1U reference scenario and the first power unit of the integrated system decreases from 80% to the 37% for the sixth power unit of the system. This trend is a consequence of the process of increasing the share of debt money being implemented in accordance with the roadmap of **Table 3** where the fraction of the debt in financing of the construction of the power units has increased from 4% for the first power unit to 50% to the six power unit. At the same time, the fraction of the debt in the structure of electricity cost of the whole system remains rather small comparing to the fraction of equity. This is due to the fact that payments to creditors are formed directly for the current unit of the system while a long-term return to shareholders is passed on to the current power unit from the all previous ones with high fraction of equity. After the completion of the system deployment, there is no more need for investing into new construction but, however, the tails of long-term payments remain. These tails make up a share of 37% of equity in the electricity cost structure after completion of the system construction.

The cost-income model used in the test calculations of the potential of the shareholder income growth under fixed selling cost calculates not only expenses, but also the profit of shareholders additional to the payouts on shares. It can be seen in the **Figure 4**, that growth of the revenue fraction in the electricity cost can be very significant: from about 18% for the first power unit of the system to more than 40% when the deployment of the system is completed.

The obtained results show some prospects for increasing the efficiency of investing to nuclear power in the option based on a system of SMRs. Implementation of the options discussed in the chapter will require the use of innovative approaches and tools for managing financial flows from various sources of investment: not only from the funds of public (state) or large energy companies, but also from the banks, investment companies and funds, including private. The expansion of the range of nuclear energy investors will contribute to the recognition by public role of nuclear power as an economically viable energy business.

4. Conclusions

Achieving the goals of the innovative development of nuclear power depends not only on technical and technological progress, but also on the creation of new institutional approaches that could have done it possible to increase the commercial attractiveness of the nuclear electricity generation option and expand the number of its stakeholders. The discussion in chapter is focused on the idea of shifting the evaluation of the nuclear power economics from the scale of one power unit to the scale of a holistic system of such units. As an implementation of this idea, the concept of a financially integrated system with several SMRs—a network structure with unified management and finances—is introduced in the chapter. To carry out numerical calculations of the system cost of electricity, a matrix cash flow model was developed.

As was established theoretically and in the analysis of calculated data, the main mechanism for enhancing economic performance of the financially integrated nuclear power system is progressive increase of the fraction of short-term investments, which under sufficiently short times between the construction of reactor units, do not transfer part of the return on investment from the constructed units to subsequent ones, thus reducing the component of the investment return in the cost of electricity with an increase in system capacity. These short-term investments consist of the debt and accelerated return of equity capital. The test calculations have demonstrated that the joint use of the short-term return on debt and equity results in gradual decrease of the electricity cost generated by the system. This effect can be directly used for enhancing the competitive ability of the nuclear option of the electricity generation.

Another option for the use of the effect of the electricity cost decreasing potential of the financially integrated system is increasing of the income of shareholders by transferring to them the revenue coming from the difference between constant purchase prices in the market and the declining electricity cost generated by the system. The perspective for essential increasing the income of shareholders and acceptable conditions for involvement of wide range of credit investors provided by financially integrated power system with SMRs can contribute to positive image of nuclear power as sustainable option of energy supply and economically viable energy business.

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Chapter 5

Teamwork in the Main Control Room

Márta Juhász and Péter Kabai

Abstract

This chapter is about the characteristics of main control room's teams. In a hazardous working environment, human factors play a key role. The quality of teamwork affects people's psychological well-being, which has an impact on the quality of their work and their ability to work safely. In Hungary, at Paks Nuclear Power Plant, we have developed a questionnaire that is able to measure the main control room's teamwork. In our paper, we present the structure of this questionnaire and define the scales created. We also base the development of teamwork on the analysis of video footage of a simulator exercise, which also highlights the characteristics of successful teamwork. Both tools can be used to understand, analyze, and then improve control rooms' teamwork for more effective collaboration and performance.

Keywords: teamwork, team mental model, leadership, explicit-implicit communication, teamwork development

1. Introduction

The four units of the Paks Nuclear Power Plant are operated by six-shift teams/crews in three eight-hour shifts per day. In one shift approx. 90–100 employees work together in the operation, which requires significant coordination and teamwork from them. Plant control is operated by five people working in the main control rooms per unit. A total of 24 main control room's teams work for safe operation. With our work, we aim to set up an operational model in the unit controller of the Paks Nuclear Power Plant and to identify the human aspects of teamwork. Based on the operational characteristics of main control room's teamwork we can support and develop them in their work.

Incident investigations revealed that there were "deficiencies in the effectiveness of the teamwork of the personnel cooperating in the execution of the activity." But what does all this mean in this unit commander work environment? In this chapter, we examine the criteria by which teams can be distinguished based on their performance, efficiency, and overall success.

2. Criteria for successful teamwork

We started our research by conducting interviews with operating director, heads of various departments, and heads of sections and "operational" managers such as unit shift supervisors and plant shift supervisors in the organization (N = 35). In the interview, they had to characterize the 24 main control room's teams based on their own thinking and insight. We analyzed this "thinking out loud" and collected the criteria behind the characterization. Since the leaders and managers participating in the interview represent the organization itself, they have a significant impact on the organizational culture formed by managers and subordinates [1–3].

Analyzing the interviews, we grouped the success criteria of unit commander teamwork into three characteristic categories: 1) characteristics related to the execution of tasks and work; 2) relationship characteristics between team members; 3) characteristics related to the team leader (Unit Shift Supervisor, USS).

2.1 Teamwork characteristics related to the tasks

In high-risk environment, production is typically based on teamwork. It is important that team members have a similar attitude to work and respect the rules. In order to be aware of what is going on at any given moment, it is important to keep each other informed and to share information in a coordinated way [4]. It is important that the team establishes a working pattern (norm) that allows them to work in a unified way.

- If someone makes a mistake during the exercises on the simulator, they draw each other's attention to the mistakes as a way of learning.

- If a mistake occurs, it is handled well: they take responsibility, admit it and stand up for each other.

- The tasks are carried out in good quality, there are no large amplitudes in their performance.

- Before starting work, they discuss the tasks: they consider, talk through the steps, prioritize, and only then start the task.

- They discuss the events together after the shift, learning the lessons.

- The knowledge of the team is constantly developing and is formed together.

- Team members share the information they have with each other.

- Team members are motivated to solve the tasks in front of them.

- There is open communication within the team regarding gaps and performance.

- Each member of the team is aware of their role, tasks, and responsibilities in the team.

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2.2 Relationship characteristics in teamwork

Failures can also occur because of poor relations between team members, and a bad atmosphere in the team. A good team atmosphere means that members dare to ask questions and dare to share their doubts. A good atmosphere in the team gives a sense of psychological safety and that trust is working. The feeling of group efficacy, which is the belief of the members that the team can perform well in a specific task. The more members feel this, the more motivated they are to work hard as a team to achieve goals [5, 6].

- Team members know each other well and are aware of each other's skills.
- They are aware of each other's weaknesses and accept each other accordingly.
- They accept each other's values.
- They are not each other's friends, but they treat each other fairly and have respect for each other.
- There is continuous back-and-forth communication between team members both vertically and horizontally.

2.3 Characteristics related to the team leader

The success or failure of a team depends not only on the skills and competencies of individuals but also on how they can synchronize and coordinate them. The "interface" between the leadership and the team process forms an inseparable integrity and together they influence team performance [7, 8].

The leader obtains, organizes, and evaluates the necessary information for the team by continuously monitoring and observing the team's external environment. With the information obtained, the leader identifies the steps needed to accomplish the task and uses this information in problem-solving. The leader communicates his/her plan to accomplish the task, while team members formulate and share an accurate model of appropriate behavior. Leader briefing has a major impact on the way the team thinks and reacts to unexpected events. The sharing of information by the leader provides the team with a knowledge structure that facilitates task solution and team adaptation to the novel, unexpected event. The leader's communication shapes the accurate model in the team members and the more specific the information conveyed, the more shared and accurate the shared mental model will be in the team, which indirectly influences team performance [1, 3, 9].

- "Every team is like its team leader."
- In a normal situation, he or she explains to the members what the objective is for a potential breakdown and discusses the operational strategy;
- The USS stimulates dialog between disciplines;
- USS initiates discussion on how to work together in the unit control room;

- The USS initiates a discussion of the events and lessons are learned together;
- At the end of a successful day, the USS provides feedback on teamwork;
- USS encourages members to learn from each other;
- USS gives positive feedback to members with the aim of improvement.

2.4 Not every group is a team, but every team is a group

We often use the terms group and team as synonyms (crew, brigade). A group is usually formed from the bottom up, held together by similarities, values, and sympathy between members, while a team is often discussed in a workplace context, and therefore typically formed from the top down, with everyone having their own functional roles, responsibilities, and a common purpose holding the team together.

Rapid technological change and the increase in the complexity of organizations have resulted in a shift from individual work toward teamwork, as the expert teams that ensure operation are made up of specialists who are trained and socialized for several years to solve the set tasks to the best of their ability. However, the knowledge required to solve the tasks alone is not sufficient for the safe operation. Teams must coordinate their knowledge gained at the individual level in order to make effective decisions and adapt to dynamically changing environmental conditions. For coordinated cooperation, they must also be able to manage social processes such as leadership, communication, and coordination. The organizational culture prepares these teams to respond adequately to unexpected events and complex problems [10, 11]. In such situations, it is almost a matter of "life and death" how team members can cooperate, how they share information among themselves, how they coordinate the pieces of information available to them, how they communicate with each other, how much they understand each other's communication, how much they trust each other, and how much they accept each other each other's point of view or each other's personality. These unexpectedly appearing, often ambiguous, information-deficient situations have a significant impact on the functioning of teams, which can be observed mostly in the behavior and communication of the members [12–14].

3. What is teamwork in high-risk environment?

In a high-risk working environment, not only the wider national culture but also the organizational culture itself expects a lot from teams, and therefore puts a lot of pressure and responsibility on the people working in the teams. A high-risk work environment is one in which employees work with dangerous technology and have a higher-than-average chance of endangering their own lives and/or the lives of others or causing significant material damage. The sources of danger can come from outside, from the environment, from the team itself, and from dysfunctional team functioning.

External sources of danger: an event that occurs unexpectedly during normal operation, which is ambiguous, possibly complex; events running in parallel; decision making under time pressure; ambiguous or conflicting information or even a lack of information; dynamically varying -often very low (monotony) or very high- task load; task load (e.g. working hours, shifts), and individual perception of workload, influenced by subjectivity (e.g. perceived workload as being greater than realistic due to fatigue or exhaustion); or the regulated, protocol-based operating mechanisms, standardized processes, resulting in low work autonomy and low potential for creativity [15–18].

Internal threats from within the team itself: in a team, members are interdependent and can only operate cooperatively, which can be tiring because some people have little willingness and ability to cooperate, so expecting them to cooperate requires a lot of energy. Sometimes the goal is not clear to all members, which leads to misunderstanding or disagreement, or even conflict. In teamwork, task conflicts may arise from a lack of agreement on how to solve a given task, and how to prioritize the steps of task execution. If a culture of conflict resolution is not developed in the team, task conflict can easily slide into the more difficult-to-manage relational conflict. Dysfunctional leadership is when the leader does not fit into the team, for example, members are afraid of an authoritarian leader, afraid to express themselves, afraid to ask questions, and unable to communicate assertively. The hierarchical structure can also generate sources of danger when a member does not dare to express disagreement with his/her leader, even when it is clear to him/her that he/she is making a mistake [19, 20].

Teams working in high-risk environments and teams carrying out highly responsible tasks and activities work in a highly regulated, protocol-based working environment, to which the internal structure of the team is adapted. Medical teams tend to be hierarchical, with face-to-face interaction and communication processes that are not well defined, and with a very divided attention between team members. Pilots also have a highly hierarchical team structure, with face-to-face interaction and a very controlled communication process. Power plant operator teams are less internally hierarchical, with everyone being an equal member of the team representing a particular area of expertise, but communication between them is also very regulated [21]. Hierarchy is defined as a legitimized power distance between the leader and the subordinates, in which the leader at the top of the hierarchy has more privileges because of his power, which the subordinates accept and maintain through their behavior [10]. In such a structure, subordinates are dependent on managers, and less autonomous, because all decisions are expected from above, so in this system, the individual learns "learned helplessness," that he is taken care of by managers. Consequently, over time, it undermines questioning, independent thinking and creativity, and undermines proactive, initiative behavior.

If we consider the worst-case outcomes of the various expert teams, the damage caused by the disorganization of the surgeon teams is relatively moderate, as "at most" is responsible for the death of the patient, but not for a national disaster. More damaging are the pilots of passenger planes when their internal functioning is disrupted and they fail to understand each other in an emergency and communication fails, as the plane could crash with the crew and hundreds of passengers on board. In comparison, the operator teams of nuclear power plants can cause the greatest catastrophic disaster, as the occurrence of such a disaster can pose a major threat to human life and the ecological balance of our environment, and our country.

3.1 Team mental model (the role of the team mental model)

Sexton's saying that "*Better the Team Safer the World*" is very true for the nuclear environment [19]. For main control room's teams to work in a coordinated way, they need to address social processes such as leadership, communication, and coordination, in addition to the professional knowledge that the members possess individually, because these social processes allow them to shape their functioning and adapt to different environmental factors. The situational factors for teams in a power plant are typically normal operation, emergency events, and major repairs [22, 23].

In the main control room teams, as "expert teams,"members represent an individual area of their professional field and in order to achieve a common goal they are performing complex activities while making a significant cognitive effort, constantly monitoring the display, sensing emerging stimuli and changes, anticipating possible situations, thinking in "*if…, then…*" contexts. Successful teams are able to align the knowledge held by their members, the information they hold, and their focus of attention, thst is, their cognitive processes, and thus create a platform, for example, "*being on the same page,*" [24] and common ground [25]. In this way, members have an individual-level mental model, which contains long-term, stable elements of declarative, procedural, and strategic knowledge about the task and the team, and their semantic organization, which converge into a team-level mental model during interactions between members and during the various team processes [26, 27].

The team mental model is a characteristic of well-functioning, effective teams that have an organized understanding, a shared understanding, a mental representation of the task (task-related mental model), and of themselves as a team (team-related mental model). The *task-related mental model* includes knowledge elements such as the characteristics of the task to be performed, for example, its structure; knowledge of the goal to be achieved, clarity; the way, order, and priority of its execution; the necessary tools, information required; knowledge of who has the relevant information [28]. A *mental model of teamwork* includes elements such as the roles and responsibilities of the members; the depth of knowledge, skills, training, and experience of the other; the typical response of the other in normal operational situations and in emergencies; the typical behavior patterns, communication, and motivation of the other [12, 29–34].

Teamwork strategy meetings, exchanging information with each other, and discussing points of view, are all situations that serve to help members get to know each other, and each other's reactions and develop a common knowledge of each other (team-related team mental model). The same happens in relation to the task, when every single team member develops a mental representation of the elements of the task, of the solution to the problem, which they share with each other through a team process such as communication, as their knowledge converges and a team-specific way of solving the task emerges. These team processes serve to bring together individual-level representations and integrate them into a team-level representation (task-related team mental model) [26]. If a team is prevented from discussing their operating strategy, or if they themselves do not practice it, the mental model is damaged, which may lead to overload and loss of energy in the team's functioning, which may eventually lead to failure.

3.2 Explicit and implicit communication

In the development of the mental model of the team, explicit communication and coordination is a direct communication with a clear purpose, and therefore leaves no doubt in the minds of the members: everyone has a clear picture of the intention and motivation behind the other's communication. This is especially necessary in new tasks, in new situations, where the mental model is not yet established, not precise enough, or not shared enough among the members, so they need to build consensus in order to organize their activities. This explicit communication requires an extra effort on the part of the team that lasts until a stable mental model is established between team members [10, 28, 35]. The team leader plays a crucial role in explicit coordination, acting as a "conductor" to coordinate team members and the information they share. This explicit communication, which requires extra energy, is possible under lower task loads, such as normal operations, when the team can devote time and attention to each other and to discussing strategy. This is a good way to prepare for a possible emergency when they have to work under more pressure in a focused, energy-saving mode. Knowing the rules and following them also stimulates collective thinking among team members. This is impersonal coordination, such as rules, protocols, standardized processes, procedures, policies, manuals, etc. at organizational level.

In an efficient, i.e. well-coordinated team in the emergency/abnormal situations that implicit communication can be observed, when everyone knows their job, their tasks and actions are well harmonized, with smooth and seamless overall work. These are barely noticeable behavioral and communication manifestations in the team, which operate with relatively low effort. This requires that members know and understand each other, and that goals and roles are clear and unambiguous, that is,. that there is a common understanding of the task, the situation, and each other, of each other's knowledge and skills.

Implicit coordination occurs when the team already has a shared mental model and can rely on it to coordinate its activities with relatively little effort. Teams that are able to coordinate their work in a resource-efficient mode are more effective in dealing with unexpected events. When the team has a shared mental model of the task, themselves, and their schedule, there is less need for explicit communication, because the model allows them to anticipate each other's needs, to know who is going to do what at a given moment without explicitly discussing it [34, 36, 37]. In implicit coordination, team members spontaneously and voluntarily inform each other and the leader of an event that is about to happen, without being directly asked to do so. The anticipation rate (AR), developed through observation and analysis of teams, is the ratio of the amount of information volunteered to the amount of information requested [10].

High-performing teams are characterized by their ability to adapt their structure, decision making, and coordination strategies to change, and thus to adapt flexibly to stressful situations [2]. In these situations, teams need to make the best use of their knowledge while minimizing the risk to safety. The importance of all this makes sense in a sudden change of situation (e.g. crisis, emergency) when under high task load and time pressure, it is no longer possible discuss strategy, but when implicit communication based on the shared mental model is needed, which is an energy-saving mode. In effective teams, implicit coordination and communication are observed to be the most effective way of dealing with unexpected/abnormal events, because it reduces overt communication, reduces effort, and allows the energy released to focus on the task at hand [10, 19, 28, 38–40]. **Table 1** below shows examples of explicit and implicit communication.

4. Characteristics of teamwork at the Paks nuclear power plant

Above, we have described the role of the team mental model as one of the most important characteristics of expert teams, which is efficient coordination and

Characteristics of explicit communication	Characteristics of implicit communication
Before starting the task, discuss and prioritize the steps. Ask for and give information openly and explicitly. Specific issues to be discussed. Information summarized by someone on the team. Issuing an instruction, acknowledging receipt of the instruction, and giving feedback on the execution of the instruction (3-way communication). Open request for assistance and help. Discussion and processing of what has happened. Establish predefined, standardized communication elements and rules.	Giving unsolicited information: if someone in the team feels that their partner needs more information, they can give it without being asked. Unsolicited actions, actions to make things go more smoothly, for example, spontaneous assistance, spontaneous information. Expression of intention to act (e.g. gesture, facial expression). Silence: the work is going smoothly and members are participating. Chat: a conversation not closely related to work, used to establish personal contact. They can openly ask each other for help and are not ashamed to do so.

Table 1.
Explicit and implicit communication in the team.

problem-solving for the team. As most organizations in which production is based on teamwork define their teamwork model, the management of the operations division of Paks Nuclear Power Plant has developed the operational characteristics of the main control room's teams, creating a culture-specific definition of teamwork.

4.1 Teamwork definition of the main control room's crew

The main control room's crew is an operational control team, led by the unit shift supervisor and consisting of the reactor operator, the senior turbine operator, the turbine operator, and the chief electrician operator. They perform their work in a physically defined location, the main unit control room. The teams work in continuous eight-hour shifts; they are not allowed to leave their workplaces until the shift has been completed and the shift has been handed over. The **Figure 1** shows the team structure.

Each team member represents one area of expertise and is also the leader of the team members working in their own professional fields, who carry out their duties for the whole unit in addition to the leader. The 2015 INPO (*Institute of Nuclear Power Operations*) considers each team member as a leader, not just the unit shift supervisor [41].

Each member needs to understand their own leadership role, which contributes to the success of teamwork. Main control room's team, together with the other subteams they manage, form a "*multiteam system*" [42]. In this sense, they are able to perform both executive and supervisorial tasks coordinating specialized tasks.

Together, the team in the main control room and the teams that operate the nuclear power plant as shift operational staff, with the engineer on duty being the leader of the staff working a shift as plant shift supervisor. The members of a shift collectively create more value as a result of their work than the numerical sum of the results of the members' work alone (the group is more than the numerical sum of the members).

4.2 Team mental model of the main control room's crew

Main control room's team members represent a specific field of expertise and have well-defined professional competencies. The knowledge possessed by each of them is

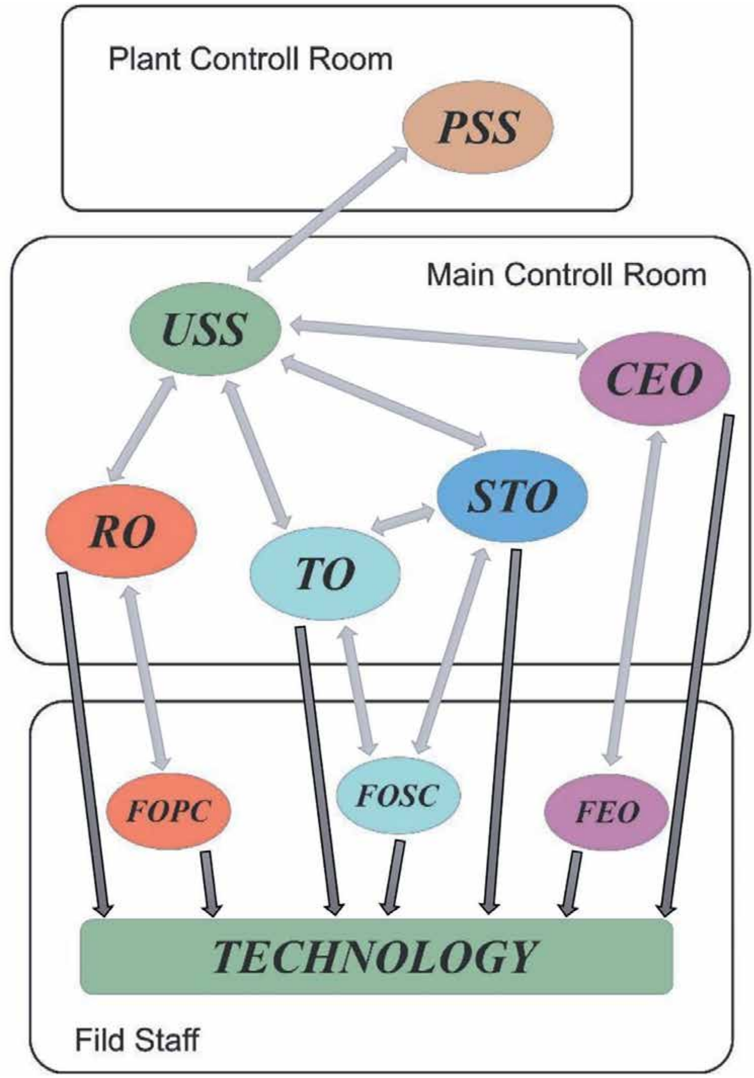

Figure 1.
Main control room's team/shift personnel (plant shift supervisor, PSS; unit shift supervisor, USS; reactor operator, RO; senior turbine operator, STO; turbine operator, TO; chief electrician operator, CEO; field operator of primary circuit, FOPC; filed operator of secondary circuit, FOSC; field electrician operator, FEO).

unique and distinct, but complementary, that is, their knowledge is complementary to each other to form a coherent knowledge base, which is needed to operate the unit together.

The members are interdependent and interdependent on the information and knowledge available to them, but each is able to work independently in his own field.

Figure 2 shows the degree of overlap in the areas of competence represented by the members of the team. Overlapping areas vary greatly in size and characteristics. The unit shift supervisor's knowledge is comprehensive across all disciplines, but the person in charge of each discipline carries out the tasks using his own professional competencies. However, in addition to the overlap between the specialized areas, there are also "white spots," which may not be covered by any of the specialized

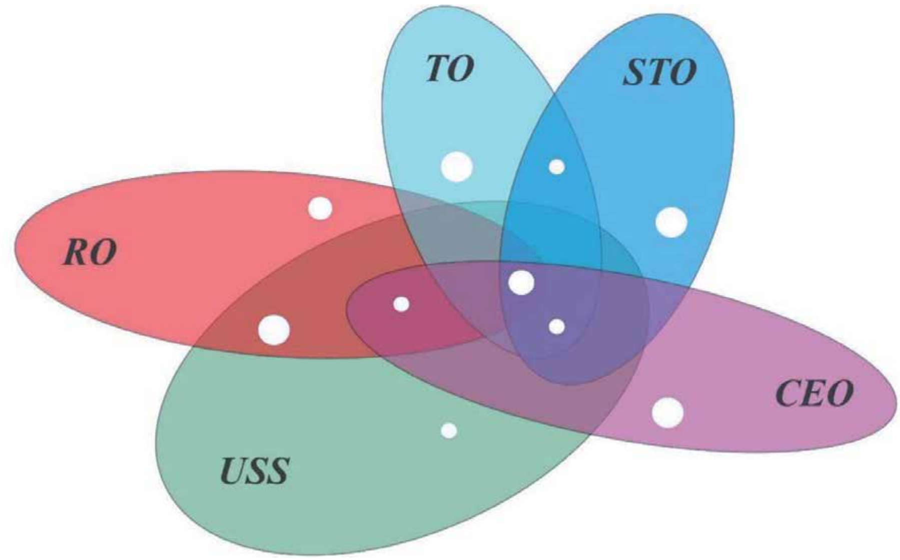

Figure 2.
Team mental model of the main control room's crew.

areas and which appear as gaps or "contamination" in the functioning of the team. For example, if members do not know each other well enough, they do not know each other's reactions, which can lead to various disturbances and anomalies in the teamwork.

5. Teamwork development at the Paks nuclear power plant

At the Paks NPP, production depends on the control room's teams, so it is very important that the internal, structural operation of the teams is not a potential source of failure. We pay particular attention to identify and monitor the functional characteristics of these teams and to develop and support teamwork. By identifying the cornerstones of teamwork, we have created a teamwork questionnaire that is able to measure teamwork in the control room along four broad areas: 1. the individual characteristics of the team members; 2. the task awareness of the team as a whole; 3. the group-atmosphere, psychological safety, and 4. the perception of the team leader's leadership style.

In our current operating model, this questionnaire is completed online by the teams, team members every 2 years, and the results are then processed jointly.

The results are used to produce a written feedback report, including the aggregated results of all five participants, which is shared with the USS and the team members. We work with the teams each year, but the focus of the actual training is based on the results of this questionnaire, so each team has a different training content in agreement with the USS. Overall, the teamwork questionnaire scales are able to cover the characteristics of effective teamwork.

At the Paks Nuclear Power Plant, the development of the main control room's teams is the result of interdisciplinary cooperation. The task of a work and organizational psychologist is to design the questionnaire, record the questionnaire, and then design a training program based on the results. As we have observed, the development training program is more accepted by the teams and results in a greater commitment to development and learning if, in addition to the work psychologist, an expert in the field is involved as a cotrainer. Therefore, another part of the development work for the teams is carried out on the simulator, where a well-considered scenario was selected and videotaped and the co-trainer cuts out scenes that give feedback on the teamwork. The selected scenarios were evaluated with every single team, together with the five team members. We cut out scenes where teamwork was more and more effective than individual professional performance or where, due to the lack of teamwork, individual professional performance was less effective than the performance of a well-functioning team. The aim of the video analysis is to reveal the success criteria ("cornerstones") of main control room's teams by identifying and highlighting good examples for the teams to become aware of. We believe that these positive examples will be more conscious and deepened through teamwork.

The scenarios were designed to require the team to perform normal operator tasks in compliance with the applicable procedures. The execution of the tasks does not produce the expected result due to programmed deviations, so based on the information available and shared, teamwork, the application of operator fundamentals and the operational decision-making plays an important role in the detection and management of the deviations.

In the next section, we present the design and structure of the teamwork questionnaire we created, as well as describe simulator exercises and highlight the parts that concerned the evaluation of teamwork.

5.1 Exploring teamwork of the main control room's crew by questionnaire

At the Paks Nuclear Power Plant, we have created a teamwork questionnaire that specifically explores the characteristics of teamwork in the control room's teams. The structure of the questionnaire is based on the scales, which are also the cornerstones of the teamwork characteristics that we have developed in advance. The questionnaire provides valid feedback to the team leader and to the team as a whole on the characteristics and features of teamwork. The questionnaire was taken twice with the staff (in 2020 and 2022) and the reliability indicators were developed accordingly and are reported in brackets next to the scales.

5.1.1 "Who am I …"

The first part of the questionnaire is entitled "Who am I?". It is an introductory questionnaire that measures at an individual level the members' "psychological capital," a complex concept [43–46]. The elements of psychological capital contribute to job performance, psychological well-being, and satisfaction in a mutually reinforcing way. As a psychological resource, it has an impact on the team [47–49] (**Table 2**).

5.1.2 "Towards the goal"

The second part of the questionnaire is called "Towards the goal" because it is about how each team member perceives the team as a whole when they are working on a task. It measures whether the member perceives the cohesiveness of the team while working, how smoothly they can work, and transition from normal work to sudden changes in work, such as a breakdown. The questionnaire also asks to what extent the individual perceives that there is a "common ground" on which they are

Scale' name (Cronbach Alfa)	Definition of the scale
Self-efficacy (.77)	Self-efficacy is an indicator of how confident and assertive you feel in your work and the team you work in.
Hope (.66)	Resourcefulness indicates how much you trust your own resources when you are stuck in your tasks.
Resilience (0.60)	Resilience indicates how you view your difficulties, perceiving them as temporary.
Optimism (.68)	Positive thinking means "realistic optimist." It indicates the extent to which you expect a positive, "good" outcome in different situations that are unknown to you.
Autonomy (.64)	Autonomy means autonomy and a sense of empowerment. It indicates the extent to which you feel independent and autonomous in carrying out tasks and making decisions.
Ambition (.86)	Ambition indicates that you are keen to constantly improve your professionalism and strive to be judged well by others.

Table 2.
Scales and definition of scales of "Who am I" questionnaire.

Scale' name (Cronbach Alfa)	Definition of the scale
Positive team functioning (.85)	Indicates the extent to which you, as a team member, perceive that the team has developed habits that help the team to be more efficient and effective in carrying out tasks.
Cohesion (.85)	It indicates the extent to which you as a team member perceive team cohesion and team unity in different task situations.
Tas-awareness (.85)	It indicates the extent to which, as a member of the team, you perceive that you are working as a unit when you are at work.
Adaptability (.85)	It indicates how well you, as a team member, perceive that the team can adapt smoothly to sudden changes in situations without disruption or loss of energy.
Shares mental model (.77)	It indicates the extent to which, as a member of the team, you perceive a "common ground" between the members, a common mindset.

Table 3.
Scales and definition of scales of "Towards the goal" questionnaire.

building and which holds them together when working and helps them to work in a more "energy efficient" mode [10, 50]. The opposite of this is when the member perceives that they are uncoordinated when working and therefore lose energy (**Table 3**).

5.1.3 "Connecting links"

The third part of the questionnaire is called "Connecting Links," which measures how the team members perceive the relationship between them, and how they perceive the atmosphere in the group, which is very important for their daily mood [35, 51, 52]. The scales of the questionnaire measure how well members perceive a positive, accepting atmosphere in which there is trust between them; how fairly they treat each other, whether they can rely on each other for attention and help; and how committed they are to the team (**Table 4**).

Scale' name (Cronbach Alfa)	Definition of the scale
Positive, accepting atmosphere (.95)	It indicates how much you feel accepted and emotionally safe as a member of the team.
Respectful communication (.83)	It indicates how respectfully team members communicate with each other.
Trust (.88)	It shows how much confidence you have as a member of the team in your colleagues' professional knowledge, skills, and commitment to what they have agreed.
Helpfulness (.77)	It indicates how much you, as a member of the team, feel that your colleagues are looking out for you in a situation where you need help.
Commitment to the team (.85)	It shows how much you like being part of the team.
Commitment to organization (.92)	It indicates how satisfied you are as an employee with the organization and the management's decisions.

Table 4.
Scales and definition of scales of "connecting links" questionnaire.

5.1.4 "My leader"

The last, fourth part of the questionnaire is entitled "My Leader is the Unit Shift Supervisor," in which members rate on the basis of the supervisor's leadership qualities [53–57]. The scales of the questionnaire measure how the members perceive the USS's leadership behavior, how much the supervisor deals with the members, and the members' individual requests. As a supervisor, it is very important to inspire and encourage people before a task, to monitor the work of the members, to listen to each member of the team, and to set guidelines and standards for them. In addition, the USS also fills in the same questionnaire about himself, only in this case the questions are in the first person singular (**Table 5**).

5.2 Observation of main control room's teamwork on the simulator

The name of the simulator scenario, which we recorded on video: *Taking the bleeding pump of the turbine low-pressure preheater into operation after overhaul.*

In the simulator exercise, the turbine operator crew has to start up the bleeding pump of the low-pressure preheater two of the odd-numbered turbine of a VVER 440 nuclear power plant, and set the nominal pipe connection of the turbine for 100% power. In this exercise, a number of preprogrammed deviations have burdened the work of the staff. These deviations are as follows:

- the manual shut-off valve on the discharge line of the "bleeding" pump has failed (the valve seat is broken off, and the valve has no flow in the open position);
- the shut-off valve on the bypass line on the low-pressure preheater main condensate side is out of order, and cannot be opened;
- and also the level gauge of low-pressure preheater four will fail during the exercise, causing the preheater to close on interlock operation (due to the failed bypass valve, the turbine will lose main condensate water supply to the feedwater tank.)

Scale' name (Cronbach Alfa)	Definition of the scale
Leading by example (.91)	It shows how much you, as a team member, consider the professionalism and behavior of your unit shif supervisor in everyday life to be exemplary and worth following.
Individual treatment (.82)	It indicates how much you, as a team member, feel that your unit shift supervisor is interested in following and supporting your work.
Inspiring, motivating (.87)	It indicates how much you, as a team member, feel that your unit shift supervisor involves you and asks for your opinion on issues that he or she knows you are competent in.
Monitoring-Developing (.81)	It is an indicator of how much you, as a team member, feel that your unit supervisor encourages and encourages you with positive feedback to improve and feel successful in your work.
Setting guidelines and norms in the team (.62)	It is an indication of how much you as a team member feel that your unit shift supervisor is striving to set operational guidelines by listening to and involving you in this process.

Table 5.
Scales and definition of scales of "my leader" questionnaire.

5.2.1 Observed characteristics of well-functioning teams

5.2.1.1 Task awareness within the team

In case of teams that have developed a functional model that meets the operational requirements, the task in this simulator exercise is first evaluated by the turbine operation are involved in the implementation:

- As the first step, the administrative and technological conditions for taking the bleeding pump into operation are checked;
- The steps of the procedure for taking the "bleeding" pump into operation are reviewed and the sequence of operations is explained to the main control room personnel;
- When describing the steps of taking the pump into operation, the unit shift supervisor (USS) and the reactor operator (ROP) are getting involved in the discussion. During the overview of the specific steps, the USS inquires about the technological risks, while the reactor operator inquires about the expected changes in the primary-secondary interaction;
- As a result of the involvement, the control room peration (CRO) team works as a team to clarify the details of the task implementation, the steps to be taken in case of failure (to reset the cascade pipe connection), the impacts on the reactor and the targets for a successful implementation;
- The safety risk of starting a high-voltage electric motor is assessed by the CRO team before implementation. Here, the USS usually assesses the risk and, based on information from the senior electrician, takes into account the technological consumers that could be lost as a consequence of a failed pump start or electric short circuit protection.

- The USS determines the primary and secondary circuit equilibrium conditions for the degraded state and the reactor power required as a consequence of the expected protection operation; the target secondary circuit steam pressure; the different target power levels required for the turbines and the feedwater pump configuration required for the proper feedwater supply to the steam generators.

5.2.1.2 Task implementation with the initial deviations

Thanks to the preliminary assessment, the control of the technological conditions is fully implemented, the preheater precipitation path is switched over and when the required precipitation level is reached, and the "bleeding" pump is started with continuous communication (information) and peer-check.

The deviation detected as a consequence of the broken gate valve seat on the pipeline is quickly identified and, as the technological risks have been assessed during the prejob briefing, a quick operational decision is made to stop the pump and restore the cascade pipe connection of the precipitation path.

As a consequence of the confirming information received from the operating staff in the field (abnormal flow noise at the manually operated gate valve and hand operation without effort — assumed lost contact between the valve seat and the spindle), the USS makes an operative decision to shut off the low-pressure preheaters 2–3, which is the technological prerequisite for the repair of the broken gate valve.

5.2.1.3 Execute tasks 2–3 low-pressure preheater shutdown with additional faults

To deal with the detected malfunction, a new operational intervention (shutdown of the affected low-pressure preheaters) is required. The task is implemented as shown in the previous observation:

- As a first step, the administrative and technological conditions for the shutdown of the preheaters affected are checked and it is clarified whether or not the missing preheaters result in the turbine power output being subject to limitation;

- The complete review of the technological conditions and the implementation according to operating instructions is carried out by the secondary circuit staff, the CRO staff is informed about the degraded main condensate preheating, the change in the steam demand for the feedwater tank heating, and the consequential need to take steam from the fresh steam line through a reducer instead of turbine bleed;

- The unit shift supervisor will review the steps of implementation with the turbine operation staff, record the sequence of the steps, discuss how the turbine power limitation will be accomplished, and identify the risk that loss of additional preheaters will not permit the continued operation of the turbine.

After the prejob briefing, the reactor and turbine power regulators are adjusted accordingly (ensuring compliance with the limitation), and the heating path for the relevant feedwater tank is set from the main steam system. Subsequently, the turbine operating crew will begin to disconnect preheaters 2–3 according to the instructions. During the disconnection, the programmed fault is activated and preheater 4 becomes disconnected and the main condensate feed to the tank is also stopped due to valve fault on the bypass line at the odd-numbered turbine.

5.2.2 Observed characteristics of malfunctioning teams

5.2.2.1 Task awareness within the team

There are teams where the prejob briefing for the initial task is not complete. The functional area involved in the task prepares for the implementation as their private task. Preparation involving the whole team generally does not take place: the administrative and technological conditions of taking the bleeding pump into operation are not fully controlled, implementation comes with time pressure because there is no communication, and everyone is watching the representatives of the executing unit, so they jump into the implementation relatively quickly.

Dysfunctions:

- The turbine operator misses to ask for the pump to be energized and tries to start it;
- A failed start-up is unexpected for the staff, they are not prepared to deal with the abnormality and therefore try to deal with it on the basis of their individual knowledge.

Safety risks are assessed before the task implementation, but only formally.

Dysfunctions:

- The consumers affected by the failed power supply due to the risk of start-up is communicated by the unit shift supervisor, but no strategy is determined in advance to deal with the resulting abnormal situation;
- The USS does not define target values to help staff manage the deviation;
- The full involvement of staff is achieved during the preparation.

5.2.2.2 Task implementation with the initial deviations

Once the operations have started, the department involved in the implementation reacts to deviations at a constant step lag:

Dysfunctions:

- Sometimes the precipitation path is reset, but the pump started remains in operation for a long time without flow
- The evolving high level causes interlock operations as staff gets into time delay because they are not prepared for unexpected situations.

After the confirming information received from the operating staff in the field (abnormal flow noise at the manually operated gate valve and hand operation without effort — assumed lost contact between the valve seat and the spindle), the staff needs time to assess the situation and review the necessary actions, so the operative decision to disconnect is also delayed compared to that of well-performing teams.

5.2.2.3 Execute tasks 2-3 low-pressure preheater shutdown with additional faults

In order to deal with the detected fault, a new operative action is required (disconnection of the affected low-pressure preheaters). Even if there was some kind of prejob briefing during the previous task, the elevated situation that has developed now makes this preparation more superficial in comparison with the previous observation. The competency area involved in the implementation tends to be left on its own, increasing the pressure to perform.

Dysfunctions:

- They begin to assess the technological conditions while carrying out the technological steps to disconnect the low-pressure preheaters;
- Deviations that occur during implementation are not anticipated by the staff and require additional effort to deal with;
- When the low-pressure preheater 4 is disconnected, it is not always clear that the turbine cannot continue to operate in this way (generally the turbine is tripped due to the failed main condensate supply);
- After the turbine has been tripped, the staff is confronted with the fact that the balance between the main condensate supply to the feedwater tank and the amount of heating steam has been upset, resulting in large feedwater tank level fluctuations that the staff has to deal with;
- The situation and the time lag already evident in these cases has even resulted sometimes in the tripping of feedwater pumps on protection signals.

It is fair to say that in case of such control room operating teams, prejob briefing is observed obviously as a nonconscious activity. The risk assessment is not detailed and generally does not address technological deviations. The staff begins to put together a strategy to deal with the anomalies after their detection, so the use of documentation creates time lag. The transfer of information during task execution is not always straightforward. The feedback on the reception of information is not always provided, much information is lost and misses its purpose. Dealing with the abnormal conditions that develop requires considerably more energy from the staff, and it often depends only on individual performance as to the depth of the abnormalities that evolve from the errors and deviations. Staff activities are often not well coordinated, with mixing executive and managerial roles.

Of course, these cases also provided examples of operator interventions taking place in the right direction throughout the implementation and the handling of events was on track. However, it is clear that this takes much more energy from staff.

The appearance of error risks is significantly more frequent, with more cases of erroneous operator intervention, and sometimes higher parameter oscillations have resulted in the occurrence of protection operations.

6. Conclusions

During the evaluation of the exercises, we made joint observations with the staff on the parts of the event sequence where team performance and teamwork can be more powerful and effective than individual professional performance, or perhaps the lack of teamwork makes individual professional performance less effective than the performance of a properly functioning team.

For those teams where coordinated cooperation and effective leadership can be seen in simulator practice, it is typical that they are aware that in this combination the turbine cannot continue to operate, but the well-discussed process conditions allow for quick recognition: a higher energy heating steam on the feedwater tank, but the feedwater supply from the condenser is not available. As a consequence, while tripping the turbine, there is a sufficient amount of time for the crew to also manage the feedwater supply tank issue. Thus, despite the elevated situation due to the turbine trip, the level of the feedwater tanks remains under control throughout the event. The preheaters will be disconnected and the setting for a new equilibrium between the primary and secondary circuits will remain undisturbed. It can be seen that in these well-functioning teams, the prejob briefing is a conscious activity. The risk assessment is detailed and includes technological deviations. Thanks to their prior preparation, they have ready-made strategies to deal with any anomalies that may occur. Information transfer is consistently relevant and well-managed throughout the execution of the task. There is always feedback on the receipt of information. Team members' activities are well coordinated.

In contrast, for poorly performing teams, prejob briefing is observed as an unconscious activity. The risk assessment is not detailed and generally does not address technological deviations. The staff begins to put together a strategy to deal with the anomalies after their detection, so the use of documentation creates time lag. The transfer of information during task execution is not always straightforward. The feedback on the reception of information is not always provided, much information is lost and misses its purpose. Dealing with the abnormal conditions that develop requires considerably more energy from the staff, and it often depends only on individual performance as to the depth of the abnormalities that evolve from the errors and deviations. Staff activities are often not well coordinated, with mixing executive and managerial roles. Of course, these cases also provided examples of operator interventions taking place in the right direction throughout the implementation and the handling of events was on track. However, it is clear that this takes much more energy from teams. The appearance of error risks is significantly more frequent, with more cases of erroneous operator intervention, and sometimes higher parameter oscillations have resulted in the occurrence of protection operations.

Overall, we can conclude from the video analysis that the briefing of the USS has a strong influence on the development of the team's mental model in the team. The more detailed the briefing is, the smoother the team can work together [9, 58, 59].

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Chapter 6

Application of the Heavy-Weight Concrete as a Fire-Resistance Nuclear Concrete

Suha Ismail Ahmed Ali and Eva Lublóy

Abstract

The application of ionising radiations became necessary and valuable for various reasons, i.e., electricity generation, medical treatment, agriculture, industry and scientific research. Nuclear power plants are one of the most complex radiation-shielding structures. Special design and building materials are required to enhance safety and reduce the risk of harmful radiation emissions. The construction of nuclear buildings must fulfil radiation attenuation, strength, fire resistance and durability which are cost-effective properties. Therefore, heavy-weight concrete (HWC) can fulfil these requirements due to its cost-effectiveness and good physical, mechanical and thermal properties. The research aims to introduce nuclear buildings, their application and their behaviour under elevated temperatures. Also, the research aims to review the heavy-weight concrete and heavy aggregate and their essential role in developing neutron-shielding and fire-resistant materials and prove this fact through investigations. However, the aim of this research was to investigate heavy-weight concrete's physical, mechanical and thermal properties at different elevated temperatures. Whereas magnetite heavy-weight concrete is the main concern. Result showed the good thermal resistance capability of magnetite concrete up to 800°C, compared to the basalt and quartz concrete. Raising the water-cement ratio (w/c ratio) of the heavy-weight magnetite concrete reduced the risk of explosive spalling at 800°C. Whereas adding metakaolin and boron carbide improved the mechanical properties of magnetite concrete up to 500°C.

Keywords: heavy-weight concrete, aggregate, elevated temperatures, nuclear, fire resistance

1. Introduction

The construction of radiation-shielding structures is one of the most critical issues, where the designing process and selection of accurate building materials are the key factors. Nuclear power plants, diagnostics therapy, industrial and some scientific research buildings are patterns of radiation-shielding structures. Therefore, nuclear buildings are exposed to harmful radiation and high temperatures. Gamma radiation and neutron flux raise the temperature of the reactor shield.

Due to its good shielding capability, concrete has been used in the construction of nuclear buildings. There are 449 nuclear reactors in 30 countries in operation and 60 in 15 countries under construction [1–3]. However, it indicates a growing demand for the construction of nuclear buildings. Attenuation against ionising radiation, thermal stability and high strength are essential in constructing nuclear buildings.

Moreover, thermal properties and behaviour under elevated temperatures are vital in designing nuclear buildings [4]. Under normal conditions, nuclear reactors are exposed to temperatures below 100°C during their service life. However, it can melt down in the case of an accident. Recommendation from the American Concrete Institute (ACI) indicates that the temperature limitation in concrete shields is about 65°C; furthermore, other international organisations allow temperatures up to 90°C [5]. Bertero and Polivka reported that cyclic heat treatment between 20 and 150°C is more damaging to concrete [6].

2. Properties of heavy-weight concrete at high temperatures

The fire resistance of heavy-weight concrete is excellent compared to other construction materials. Therefore, it can be used as a fire-resistant material in nuclear buildings. Its good fire resistance is owing to the aggregate and cement components. At the same time, the concrete matrix has low thermal conductivity and high heat capacity and a relatively low degradation rate at high temperatures. Therefore, concrete's heat transfer rate, mass loss and strength loss are slow. Correspondingly, the residual mechanical, thermal and deformation properties of concrete are essential to identify the fire resistance of concrete. However, constituents of concrete, such as aggregate, cement type, and chemical, mineral or nanoparticle admixture, directly affect these properties. In nuclear buildings, shielding properties are directly affected by the iron contents and the amount of fixed water [7–9].

Identifying the residual physical, mechanical, shielding and thermal properties of heavy-weight concrete under elevated temperatures is prerequisite for designing nuclear concrete (**Figure 1**).

Fire or heat influences the mechanical, physical, thermal, deformation, radiation-shielding and other material-precise properties, such as spalling in concrete. Physical changes include visual observation, porosity, absorption rate and mass loss [10, 11].

Thermal properties measured the heat transfer, while mechanical properties measured changes in the strength and stiffness of concrete. The strain behaviour determines deformation properties. Other specific material properties, such as spalling and colour change, are also important. The properties mentioned above are varied with

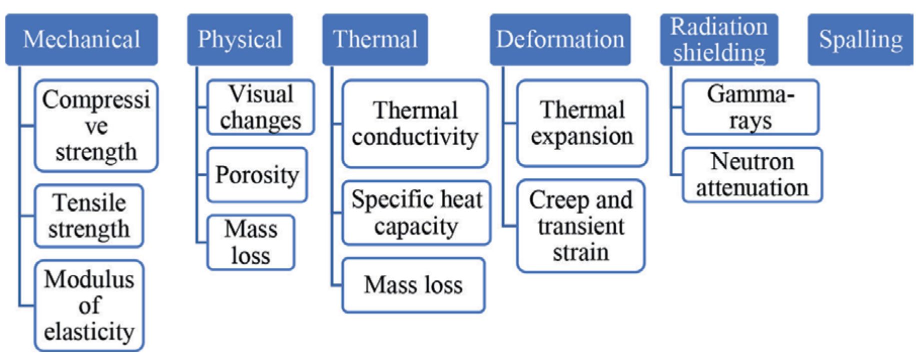

Figure 1.
Properties of heavy-weight concrete (HWC) under elevated temperatures [8, 9].

the function of temperature. Although concrete and steel are the main constituents affected by heat, the concrete ingredients and the type of steel fibre are essential [9].

2.1 Mechanical properties

Mechanical properties determining the fire resistance of concrete are compressive strength, flexural strength, modulus of elasticity and stress-strain response at elevated temperatures. In the case of fire, the remaining (residual) properties were considered [10, 11].

Compressive strength is a critical property of concrete. It depends on the mix design, aggregate type, grading and size of aggregate, water-cement (w/c) ratio and curing condition at ambient temperature. Moreover, at high temperatures, it is affected by the temperature level, heating rate and duration of heating.

The tensile strength is an essential property in concrete damage and leads to the appearance of microcracks. However, it represents 10% of the compressive strength in ordinary concrete and less in heavy-weight or high-strength concrete. Therefore, it is influenced by the same factor of compressive strength. Simultaneously, the modulus of elasticity of concrete decreases at elevated temperatures due to the degradation and breaking of the bond of the cement gel [12, 13].

Many authors study the mechanical properties of heavy-weight concrete at elevated temperatures. According to Demir et al. [14], about 58–64 MPa compressive strength was achieved using limestone, baryte and siderite aggregates. However, these values are satisfactory with the available kinds of literature. Results showed no significant loss in compressive strength at 300°C. Correspondingly, the residual compressive strength declined by 59% at 600°C [14]. Brandt and Jozwiak-Niedzwiedzka (2013) reported that the compressive strength declined by 30–40% above 100°C, while the tensile strength reduced even more [15]. Sakr and El-Hakim studied the mechanical, physical and shielding properties of baryte, gavel and ilmenite concrete at 25 up to 950°C, elevated temperatures. The study reported that ilmenite concrete has better residual mechanical properties than gravel and baryte [16]. Beaucour et al. investigated electric arc furnaces (EAFs) and steel slag as heavy-weight aggregates appropriate for radiation-shielding structures. Results demonstrated that EAF steel slag aggregates have better thermal behaviour than baryte aggregates [17].

2.2 Thermal properties

The thermal properties represent the thermal conductivity, specific heat capacity, thermal diffusivity, mass loss and density. Thermal conductivity is the capability of the materials to conduct heat, which can be measured by steady-state or transient methods [18]. Alternatively, the amount of heat required to change the temperature of the material by 1° is the specific heat. Therefore, the thermal conductivity λ and the specific heat capacity Cp are measured using the ISOMET 2104 (heat transfer analyser) device [19–20]. Several factors influence the heat capacity of concrete: the moisture contents, density and the type of aggregate. High thermal conductivity concrete has better thermal stability due to decreasing thermal stress between the inner and outer surfaces [21, 22]. Generally, the thermal conductivity of different concrete mixes ranges between 1.4 and 3.6 w/(m K), and the heat capacity between 840 and 1170 (J/kg K). Therefore, the growth in the moisture contents increased the heat capacity of concrete. According to the literature, the thermal conductivity of high-strength concrete is higher than that of standard-strength concrete [23, 24].

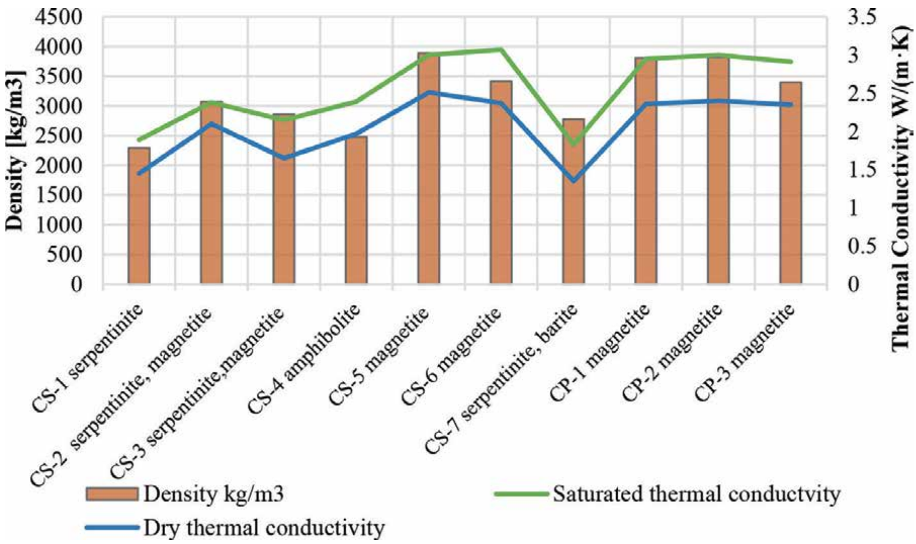

Figure 2.
Saturated and dry thermal conductivity and the density for different radiation-shielding concrete mixes [25].

Investigation of the thermal properties of nine shielding concrete mixes was studied by Glinicki et al. [25]. However, the concrete mixes contained different magnetite, baryte, serpentine and sand aggregates (**Figure 2**). His study concluded that the thermal conductivity of proper concrete falls between 1.0 and 3.6 w/(m K). Serpentine CS- 1 mix showed the lowest thermal conductivity at 1.83 w/(m K), while magnetite CS- 6 mix showed the highest thermal conductivity at 3.07 w/(m K). Therefore, adding baryte or magnetite to the serpentine aggregate improved the thermal conductivity of concrete [25].

Change in the mass of concrete occurred due to the release of the evaporable water, dehydration and decomposition of the cement paste and aggregates, and the spalling of concrete [26]. These changes develop cracks, surface spalling or even explosions of concrete [27]. Several factors influence the mass loss of concrete: the composition, porosity and thermal stability of the concrete mix. Different water-cement ratios and heavy-weight aggregate ratios directly influenced the mass loss of nuclear concrete [28]. A study was carried out by Ling, which indicated that loss in the mass of baryte-based concrete is high at 300°C. However, it is owing to the high absorption capability of baryte aggregates [29].

2.3 Deformation

When the material expands or shrinks because of the heat, it causes thermal expansion. Therefore, thermal expansion, creep and transient strains are different forms of material deformation. Thus, the thermal expansion is explained by the coefficient of thermal expansion. The coefficient of thermal expansion is a percentage deformation, while creep and transient strains are time-dependent deformations [24].

2.4 Spalling

Due to the heat treatment procedures, some pieces were separated from the concrete. Therefore, these separations are known as thermal spalling [30–31].

The separation appears sudden, violent, prolonged and quiescent, and it can be classified into general or destructive spalling, local spalling and sloughing off spalling [32]. During the heat loading test, the thermal stress increased due to the growth in the pore pressure buildup [21]. Different factors, such as the density of aggregates, the heating rate, thermal gradients and thermal stress, can develop the risk of explosion of concrete. The divergence between the cement paste and aggregates is reduced by the thermal expansion of the heavy-weight aggregates [33]. High binder content can also increase the risk of explosive spalling, so high cement amounts require more water, while adding supplementary cementitious material such as silica fume can reduce the permeability of the cement gel [31].

2.5 Radiation shielding

Concrete can be used as shielding materials for both gamma and neutron radiations. Attenuation against hazardous radiation requires high-density materials, while protection against neutrons (neutron energy/speed) depends on the atom's nuclei. In a nuclear reactor, the neutron flux is 1016–1018 n/cm2/s. Heavy elements in concrete are required to slow down the fast neutron, and hydrogen ion is necessary to absorb a neutron. Gradual heating from the shielding influences the neutron attenuation properties of concrete [34].

There is a direct correlation between the parameters of compressive strength, density, thermal conductivity/fire resistance and attenuation coefficient. However, developing these parameters can warrant the best shielding capability of the structure.

For more details, an experimental programme was carried out to investigate the magnetite heavy-weight concrete's physical, thermal and mechanical properties at different water-cement ratios and with and without metakaolin and boron carbide additives. Furthermore, it compared the thermal stability of magnetite heavy-weight concrete with those of other types of concrete, such as basalt and magnetite concrete.

3. Experimental programme

3.1 Applied material

The experimental programme tested the heavy-weight magnetite concrete's mechanical, thermal and physical properties based on different parameters. The parameters were the different types of aggregates, different water-cement ratios and different supplementary materials. The selection of ingredients for different concrete mixes relied on two main properties: hydrous aggregates' capability to slow down high-energy neutrons and the high atomic weight and amount of fixed water to attenuate gamma rays and absorbed neutrons [35–38]. The magnetite aggregates were the main heavy-weight aggregates applied to produce the heavy-weight concrete. Other aggregates, such as basalt and quartz, were tested and compared to the magnetite-heavy aggregates. Three different water/cement ratios of 0.42, 0.47, and 0.52 were examined and compared, and metakaolin and boron carbide supplementary materials were also investigated for the magnetite heavy-weight concrete. The main concrete ingredients are Portland cement, aggregates, water and admixtures. The type of applied cement is the CEM I 52.5 SR. However, it has high early ultimate strength and considerable heat evolution properties [39–42]. **Figure 3** illustrates the applied aggregates with their physical properties [37].

Figure 3.
*Different mineral aggregates and their physical properties according to BS EN 1097 [37]. * S.D. = specific density [g/cm^3], W.A = water absorption [%].*

Heavy-weight magnetite aggregates have grain sizes of about 0–4, 4–8 and 8–16 mm, while quartz concrete mix contained 22% and 36% of coarse quartz aggregates with 4–8 and 8–16 mm and 42% of sand aggregates.

Fifty percent of quartz aggregates were replaced by basalt for the designing mix of basalt concrete. **Table 1** shows the design mix of different concrete types according to the different aggregates, different water-cement ratios and different supplementary materials.

3.2 Laboratory experiments

The experimental programme includes two parts, sample preparation and laboratory experiments. Cubes and prisms of concrete specimens were manufactured using a standard mould. After the demoulding process, each specimen was cured in water for seven days. Afterwards, the samples were kept at ambient temperature until the 28th day and tested.

Every piece was subjected to temperatures of 20, 150, 300, 500 and 800°C for 2 h, with a heat rate of 1°C/min. At the same time, the heat treatment curve was similar to the ISO fire curve. Afterwards, the physical, mechanical and thermal properties were evaluated for different samples (**Figure 4**).

Physical properties include visual observations, mass loss and density measurements. After the heat treatment, pictures were taken from cooled samples; however, several measurements were taken for each specimen before and after the fire treatment to determine the difference in mass. The thermal conductivity λ and specific heat Cp measurements for the different samples were taken using a heat transfer analyser (ISOMET 2104) instrument (**Figure 4f**).

4. Discussion and results

4.1 Visual observation

Visible changes were recognised in the different concrete mixes after the heat treatment procedures. Visual changes include cracks, colour changes and spalling. As shown in **Table 2**, there are no visible changes in different concrete mixes at 150°C. However, only evaporation water was released from the sample.

At 300 C, there were no significant changes in different concrete mixes; however, only minor spalling spots were recognised in basalt and quartz concrete. Accordingly, adding metakaolin to magnetite heavy-weight concrete caused explosive spalling at

Parameters	Mixes	CEM I 52.5 N SR (kg/m³)	Water (kg/m³)	w/c (%)	Aggregate (kg/m³)	Grain size [kg/m³]					Admixture (kg/m3)	Air (l/m³)	Design Mix Density (kg/m³)
						0/4 (mm)	4/8 (mm)	8/14 (mm)	11/22 (mm)	Total	Glenium C300 60% & Glenium 51 40%		
Aggregates	MG-R	380	160	0.42	Magnetite 100%	3310				3310	13.3	15	3863
	QU-R				Quartz & sand	784	411	672		1866	2.28	10	2408
	BZ-R				Basalt, normal & sand	1098	128	183	943	2353	9.5	10	2902
W/C %	MG-I	380	160	0.42	Magnetite 100%	3310				3310	13.3	15	3863
	MG-II		179	0.47		3237				3237	9.5		3805
	MG-III		198	0.52		3158				3158	6.48		3743
Additives	MG-R	380	160	0.42	Magnetite 100%	3310				3310	13.3	15	3863
	MG-MK					3271				3271	13.3		3844
	MG-BC					3233				3233	13.3		3826

Table 1.
Concrete mix proportions.

Figure 4.
(a) Mixing, (b) casting, (c) demoulding, (d) heat treatment, (e) compressive strength and (f) thermal properties' measurements.

300°C; therefore, it increases the internal pressure and decreases the permeability of concrete. At 500°C, there are no apparent changes in the magnetite-based concrete and at different water-cement ratios. On the other hand, cracks were observed on the basalt concrete; however, these cracks were relatively more and were accompanied by explosive spalling in quartz concrete. Therefore, it explains the low thermal resistance of quartz concrete compared to those of basalt and magnetite concrete. Alternatively, at 500°C and 800°C, adding metakaolin and boron carbide caused explosive spalling in magnetite heavy-weight concrete. Therefore, supplementary materials decreased the permeability of the cement paste and rapid growth in the heat raised the thermal stress and caused the spalling of heavy-weight concrete (**Table 2**).

At 800°C, extra cracks, colour changes and surface spalling appeared on the quartz and basalt concrete. Consequently, explosive spalling was recognised on magnetite-heavy concrete, where 20% of the mass was lost. Raising the water-cement ratio of magnetite concrete reduced the risk of explosion spalling by increasing the porosity of the concrete (**Table 2**).

4.2 Thermal properties

According to the results, the thermal properties of different concrete mixes were varied, specifically in mixes with different aggregates. On the other hand, supplementary materials influence the thermal behaviours of heavy-weight concrete. As shown in **Figure 5**, magnetite concrete has a relatively high density compared to basalt and quartz concrete. Therefore, the density of magnetite concrete ranged between (3700–3750 kg/m3), and between (2400–2450 kg/m3) in basalt concrete, while it was in the range of (2350–2400 kg/m3) in normal quartz concrete. Therefore, adding

Tested parameters					
Different aggregates		**Different W/C ratios**		**Different additives**	
500 °C	**800°C**	**500°C**	**800°C**	**500 °C**	**800°C**
Magnetite		Magnetite 0.42%		Magnetite-Reference	
					
Quartz		Magnetite 0.47%		Magnetite-Metakaolin	
					
Basalt		Magnetite 0.52%		Magnetite-Boron carbide	
					

Table 2.
Concrete mix proportions.

metakaolin and boron carbide additives increased the density of magnetite concrete. There was a direct influence on the density and the thermal conductivity of different concrete mixes and their thermal stability (**Figure 5**).

However, as shown in **Figure 5**, magnetite reference concrete has relatively high thermal conductivity and density, which explains its good thermal resistance against fire up to 800°C. Accordingly, the thermal conductivity and density of basalt concrete were relatively low. Therefore, they enhanced the thermal stability of basalt concrete up to 500°C. In contrast, quartz concrete has a relatively high thermal conductivity, but lower density, which therefore weakened its thermal resistance against fire above

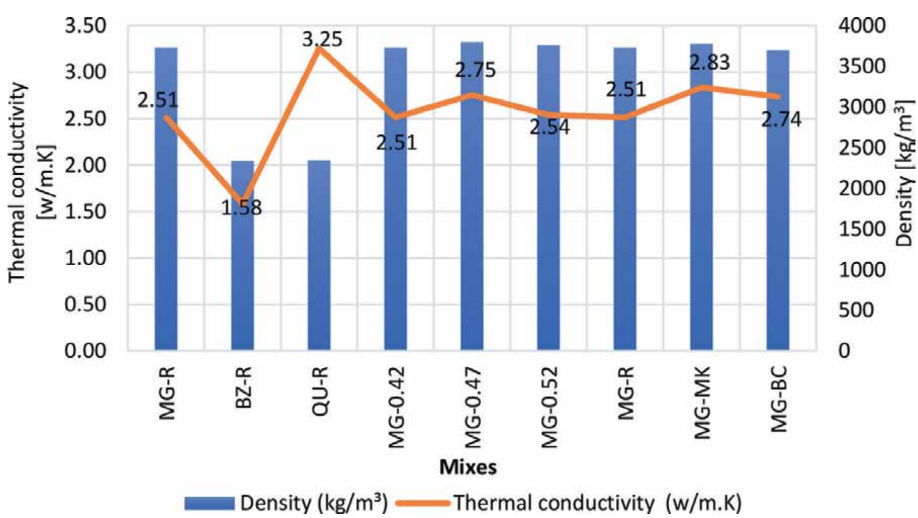

Figure 5.
Density and thermal conductivity of different concrete mixes.

300°C. Adding metakaolin and boron carbide raised the thermal conductivity of magnetite heavy-weight concrete. However, it increased the risk of explosive spalling at high temperatures (**Figure 5**).

There was a strong correlation between thermal conductivity, density and heat capacity. Concrete with low heat capacity has relatively good thermal resistance. As shown in **Figure 6**, the heat capacity of magnetite concrete was low; therefore, it explained its good thermal resistance. Accordingly, the heat capacity of basalt concrete is high despite its low thermal conductivity; therefore, it can resist heat/fire up to 500°C. On the other hand, quartz concrete has relatively high heat capacity and thermal conductivity compared to its low density. Therefore, it has weakened its thermal stability. Raising the water/cement ratio of magnetite heavy-weight concrete reduced the heat capacity. Consequently, it improved its thermal resistance, specifically at 800°C. Adding metakaolin and boron carbide increased the heat capacity of magnetite concrete; however, it directly worked on the rapid growth of the thermal stress and caused the spalling of concrete (**Figure 6**).

4.3 Mechanical properties

As shown in **Figure 7**, the compressive strength of concrete mixes varied at different concrete mixes. Therefore, at ambient temperatures, the compressive strength of quartz concrete was relatively high compared to those of basalt and magnetite concrete. In contrast, magnetite reference concrete has a relatively lower compressive strength than basalt. Therefore, it was due to the moisture content in the property of magnetite concrete. Thus, raising the water-cement ratio of magnetite concrete improved the compressive strength at ambient temperatures. Accordingly, adding metakaolin and boron carbide improved the compressive strength of magnetite concrete at ambient temperatures. Therefore, it was due to the decreasing permeability of the heavy-weight concrete (**Figure 7**).

As shown in **Figure 8**, the compressive strength of concrete mixes gradually declined after the heat treatment. Therefore, at 150°C, the compressive strength of

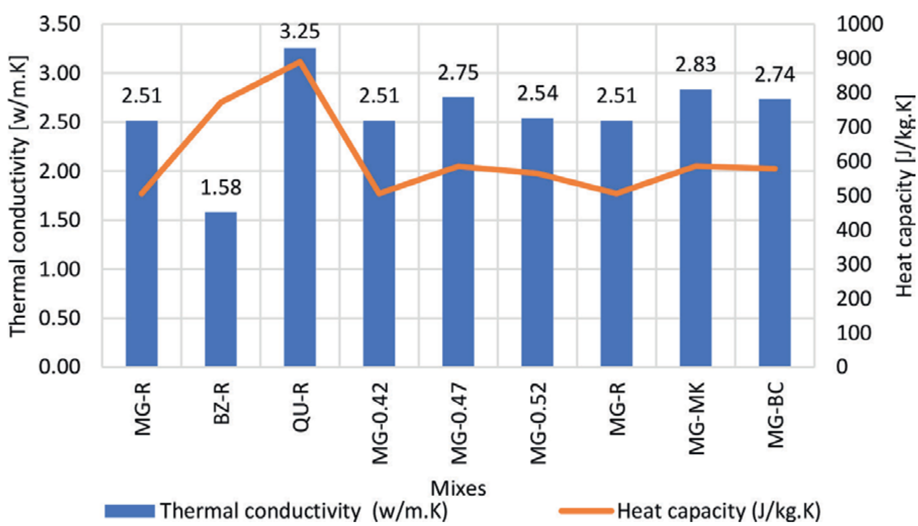

Figure 6.
Heat capacity and thermal conductivity of different concrete mixes.

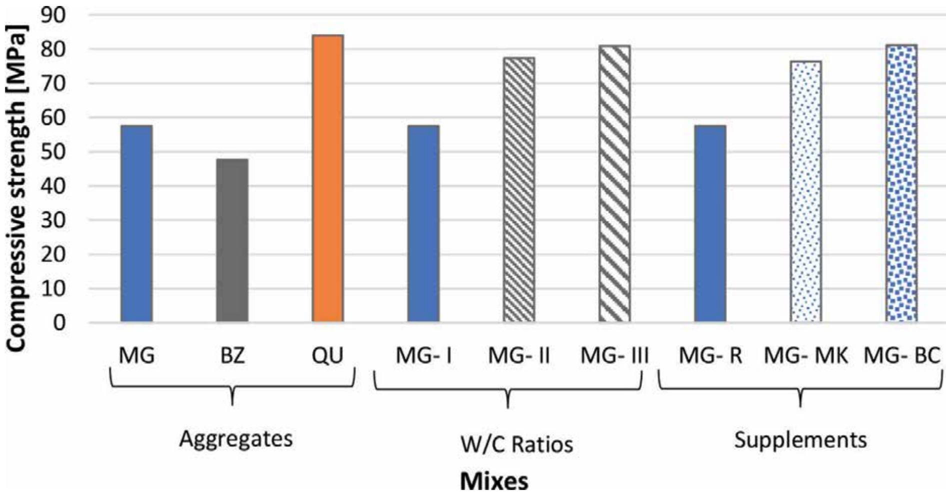

Figure 7.
Compressive strength of different concrete mixes at the ambient temperatures.

quartz and basalt concrete declined by 11 and 10%, respectively, whereas the declination rate in magnetite concrete was relatively highest by 22%. Therefore, it was due to the release of unbounded water. At 300°C, there was no significant declination in the compressive strength of different concrete mixes. Therefore, it became stable and sometimes increased due to the continuous evaporation and the beginning of the dehydration of the cement gel. Up to 500°C, the compressive strength of different concrete mixes significantly developed due to a decline in the moisture content caused by the maximum dehydration of the calcium silicate hydrates (CSH).

Moreover, the development was significant by adding metakaolin and boron carbide additives and at high w/c ratios in concrete mixes. In contrast, at 500°C, the compressive strength of quartz concrete immensely declined by 60% due to the decomposition process of the CSH. At 800°C, the compressive strength of quartz and basalt concrete steeply declined by 87 and 77%, respectively, due to the second stage of the CSH decomposition (**Figure 8**).

However, magnetite concrete has a relatively stable compressive strength value of up to 800°C. However, increasing the water-cement ratio and adding metakaolin and boron carbide declined the compressive strength at 800°C due to the high decomposition level of the cement CSH. Furthermore, metakaolin and boron carbide raised the thermal stress while raising the water/cement ratio developed the pore volume, though together, they accelerated the CSH decomposition.

As shown in **Figure 9**, at 150°C, the flexural strength of different concrete mixes gradually declined due to the evaporation of unbounded water. However, an exception was recognised in quartz concrete, due to the high evaporation level of chemically bounded water. At 300°C, the flexural strength of different concrete mixes developed; therefore, it indicates the high dehydration level of the cement paste. At 500°C up to 800°C, the flexural strength of different concrete mixes gradually declined due to the dehydration and decomposition of the CSH. However, the decomposition level of the CSH was relatively high at 500 up to 800°C in quartz concrete and at 800°C in basalt concrete. On the other hand, raising the w/c ratio improved the flexural strength of magnetite concrete by reducing the CSH decomposition level (**Figure 9**).

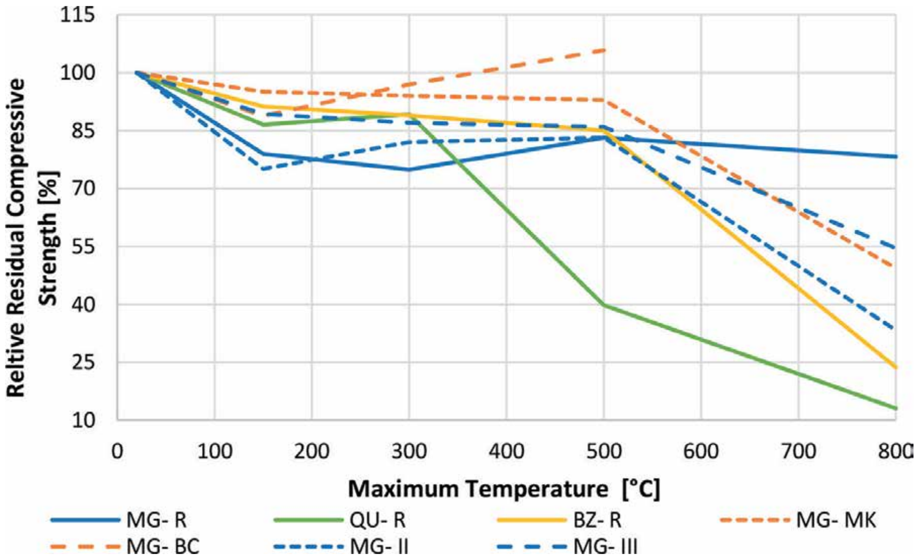

Figure 8.
Relative residual compressive strength of different concrete mixes at high temperatures.

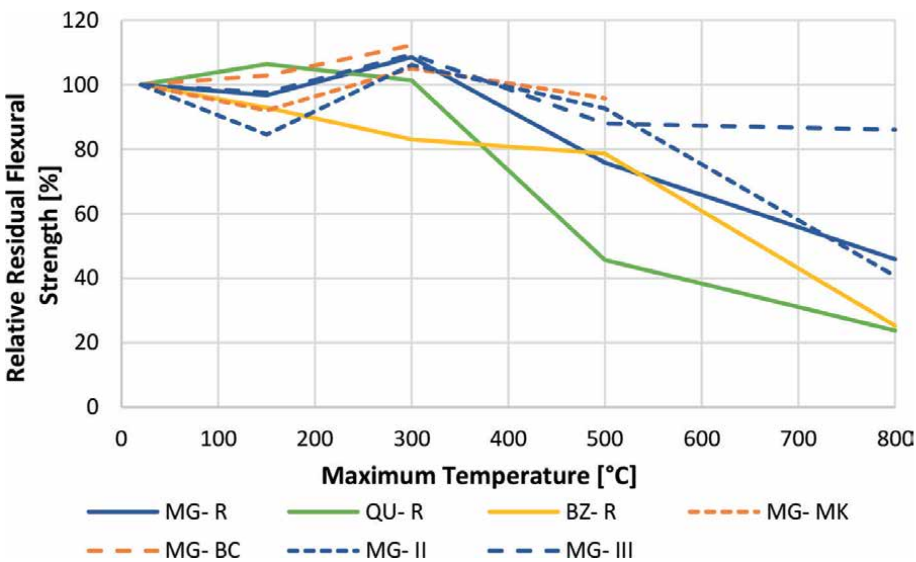

Figure 9.
Relative residual flexural strength of different concrete mixes at high temperatures.

5. Conclusion

The properties of the heavy-weight concrete at elevated temperatures were reviewed and explained. Heavy-weight concrete can attenuate hazardous radiation and has good thermal/fire resistance. In addition, it can retain the physical and mechanical properties at high temperatures. For more details, the physical, thermal and mechanical properties were studied before and after the heat treatment for different concrete mixes. Therefore, visual observation, thermal properties, compressive strength and flexural strength were investigated for the magnetite, quartz and basalt concrete in addition to magnetite at different w/c ratios and with and without metakaolin and boron carbide additive.

Due to its high density and good thermal properties, magnetite heavy-weight concrete can resist heat/fire up to 800°C. On the other hand, quartz concrete has good thermal properties up to 300°C. Afterwards, it suffers from cracks, colour changes and explosive spalling in addition to the steep declination in the compressive and flexural strength at 500 and 800°C, respectively. However, it is owing to the high and rapid decomposition level of the CSH. Basalt concrete can resist heat/fire up to 500°C due to its low thermal conductivity. Hence, its physical and mechanical properties dropped at 800°C. Therefore, it indicates a high CSH decomposition level at 800°C.

Raising the water/cement ratio of the heavy-weight magnetite concrete eliminates the risk of explosive spalling at 800°C. At the same time, it reduced the compressive strength at 800°C. In contrast, adding metakaolin and boron carbide to the heavy-weight magnetite increased the explosive spalling risk at 500 and 800°C, respectively. Therefore, it was due to the influence of the supplementary materials on raising the heat conductivity and heat capacity of the heavy-weight magnetite concrete. Alternatively, at 800°C, adding metakaolin and boron carbide accelerated the decomposition level of the CSH.

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